

Optical and X-ray profiles in the REXCESS sample of galaxy clusters^{*}

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ABSTRACT

Galaxy clusters' structure, dominated by dark matter, is traced by member galaxies in the optical and hot intra-cluster medium (ICM) in X-rays. We compare the radial distribution of these components and determine the mass-to-light ratio vs. system mass relation.

We use 14 clusters from the REXCESS sample which is representative of clusters detected in X-ray surveys. Photometric observations with the Wide Field Imager on the 2.2m MPG/ESO telescope are used to determine the number density profiles of the galaxy distribution out to r_{200} . These are compared to electron density profiles of the ICM obtained using *XMM-Newton*, and dark matter profiles inferred from scaling relations and an NFW model.

While red sequence galaxies trace the total matter profile, the blue galaxy distribution is much shallower. We see a deficit of faint galaxies in the central regions of massive and regular clusters, and strong suppression of bright and faint blue galaxies in the centres of cool-core clusters, attributable to ram pressure stripping of gas from blue galaxies in high density regions of ICM and disruption of faint galaxies due to galaxy interactions. We find a mass-to-light ratio vs. mass relation within r_{200} of $(3.0 \pm 0.4) \times 10^2 h M_\odot L_\odot^{-1}$ at $10^{15} M_\odot$ with slope 0.16 ± 0.14 , consistent with most previous results.

Key words: galaxies: clusters: general – X-rays: galaxies: clusters – intergalactic medium – dark matter

1 INTRODUCTION

Galaxy clusters are the most massive gravitationally bound and virialised objects in the observable Universe, with masses up to a few $\times 10^{15} M_\odot$ (e.g. Köhlinger & Schmidt (2014) measure the projected mass within 200 kpc of RXC J1347.5–1145 – one of the most X-ray luminous clusters found – to be in the range $(2.19 - 2.47) \times 10^{15} M_\odot$). Superclusters of galaxies can be more massive and bound, but are unvirialised, e.g. Chon, Böhringer & Nowak (2013). Galaxy clusters are interesting as their contents are reasonably representative of the contents of the universe as a whole and they contain a population of coeval galaxies whose appearance is affected by a whole range of astrophysical processes and the interactions between the processes.

The dominant baryonic component of galaxy clusters is the intracluster medium, (ICM), a hot ($> 10^7$ K), X-ray emitting plasma which contains most of the baryonic mass (e.g. Lin et al. 2003). The gas becomes X-ray luminous after being heated by adiabatic compression and shocks during cluster collapse (e.g. Gunn & Gott 1972; Kravtsov & Borgani 2012). A fraction of the clusters have a centre where the density is high and where entropies can be low enough that cooling should take place on the order of the Hubble time (Fabian 1994), but feedback mechanisms quench cooling flows (Bower et al. 2006; Fabian 2012 is a recent review), adding additional energy to the initially gravitationally heated gas and causing it to be more broadly distributed than the dark matter potential. Cluster mass profile estimates from X-ray data, including ICM density measurements, are limited to the region in which robust temperature measurements can be made. For *XMM-Newton* and *Chandra*, this is typically $\lesssim r_{500}$; *Suzaku* and *ROSAT* can reach r_{200} with

* Based on observations collected at the European Southern Observatory (La Silla, Chile).

substantially lower spatial resolution (Reiprich et al. 2013) (Δ is the ‘halo overdensity’ and r_Δ refers to the radius of the volume in which the mean density is Δ times the critical density of the universe).

Cluster galaxies can be used to probe the cluster environment to greater cluster-centric distances than gas and can be treated as approximately collisionless particles moving in the dark matter potential well of the cluster. The well known morphology-density relation – higher fractions of elliptical galaxies in high density environments like galaxy clusters, compared to low fractions of elliptical galaxies in the lower density field environment (Dressler 1984) – is caused by the ICM and the presence of other galaxies, but a precise description of the way the different components involved interact is not yet available. The critical processes are: ram-pressure stripping, where weakly bound gas is stripped away from galaxies by interaction with the ICM (Gunn & Gott 1972); strangulation, where galaxies are starved of cool gas in their haloes – gravitational heating combined with the active galactic nucleus (AGN)/wind/supernova feedback mechanisms already mentioned lead to ICM entropy which is too high for effective cooling and replenishment of the cool gas (Larson et al. 1980); harassment – gravitational interactions between galaxies which increase internal energy and lead to morphological change (Farouki & Shapiro 1981; Moore et al. 1996; Moore, Lake & Katz 1998); and galactic cannibalism, where dynamical friction reduces the velocity of satellites relative to the central galaxy below the velocity dispersion of the satellite, allowing it to be accreted on to the central galaxy (Ostriker & Hausman 1977). Galaxies at low cluster-centric distances are preferentially harassed and starved due to the high ICM density and more frequent encounters with other cluster galaxies, including cD galaxies which are often the brightest cluster galaxy (BCG). Faint and dwarf galaxies with the weakest dark matter haloes and the weakest hold on their gas reservoirs fare the worst in this environment such that the population of cluster galaxies seen at $z > 0.4$ which includes a large fraction of star forming galaxies changes by $z = 0$ into a population dominated by galaxies with very low star formation rates (Butcher & Oemler 1984; Dressler et al. 1994; Oemler et al. 1997; Popesso et al. 2006; Boselli & Gavazzi 2006).

It should be noted that an X-ray selected sample like the Representative *XMM-Newton* Cluster Structure Survey (REXCESS, Böhringer et al. 2007), used in the present study, preferentially represents objects with higher ICM densities, so we could expect that any ICM-dominated effects would be stronger in our results than in other, optically selected samples (e.g. Carlberg et al. 1997) or partially optically selected samples (e.g. Popesso et al. 2004). They also preferentially include clusters with deep potential wells and thus more time available for galactic evolution. Böhringer et al. (2004) show that cool-cores in clusters must be preserved on very long time-scales and we could expect these to cause distinctive features in the population of galaxies. Conversely, if we assume clusters which show disturbances in their X-ray morphology are relatively recent mergers, we would expect their galactic populations to be less evolved than in other types of cluster and might also show some trace of disturbance in the galaxy distribution.

In this work we study the relationship between the optical density profiles of the galaxy distribution and the dens-

ity profiles of X-ray emitting gas in X-ray selected galaxy clusters. We explore the extent to which galaxies and gas trace one-another and the underlying dark matter. We also investigate how the red and blue galaxy populations are distributed. We investigate the total mass to optical light ratio of galaxy clusters, and measure how this varies with respect to total cluster mass and morphology (presence/absence of cool-cores, regular/disturbed ICM). By taking into account the morphology of our sample, we show clear differences in the distribution of different types of galaxies in the centres of clusters which have had relatively stable morphology for a long period of time – massive clusters or those which have cool-cores – when compared to clusters with signs of more radical recent evolution – disturbed and non cool-core clusters.

The paper is structured as follows. In Section §2 the sample characteristics, X-ray data and optical data are described. In Section §3 we describe all stages of the analysis including object detection, classification, optical data calibration, red sequence fitting, radial profile generation and luminosity measurements, along with the results generated at each stage. The results are discussed in Section §4. The conclusions are summarised in Section §5.

Throughout this paper, radial distances are measured in units of r_{500} . The influence of the cluster may extend further than this, so we typically use the region outside $1.5 r_{500} \sim r_{200}$ as the off-target region. ($r_{200} = 1.51 r_{500}$ for a concentration $c_{500} = 3.2$, (Arnaud, Pointecouteau & Pratt 2007)). Magnitudes M in a given broad band filter (R, V, B) are signified by a subscript suffix, AB magnitudes by _{AB}, Johnson magnitudes by _J and K-correction by _K. We adopt a flat cosmology where $h = 0.7$ (and $h = 0.7 h_{70}$), $\Omega_m = 0.3$, $\Omega_\Lambda = 0.7$ and $H_0 = 100 h \text{ km s}^{-1} \text{ Mpc}^{-1}$.

2 SAMPLE DESCRIPTION

2.1 REXCESS sample

The REXCESS sample has been compiled as a galaxy cluster sample, representative of clusters detected by their X-ray luminosity and independent of their morphology. The sample selection is described in Böhringer et al. (2007). The clusters have redshifts between $z = 0.055$ and $z = 0.183$ and luminosities above $0.4 \times 10^{44} h_{70}^{-2} \text{ erg s}^{-1}$ in the (0.1–2.4) keV band. The r_{500} region, where the mean density is $500 \times$ the critical density, plus a region outside where the background can be estimated are within the *XMM-Newton* field-of-view ($\sim 30'$). The mass range of the clusters is $M_{200} = (1.36 - 10.8) \times 10^{14} M_\odot$. They represent a relatively homogeneous population in X-ray luminosity, L_X .

The 14 objects comprising the subset of the REXCESS sample used in this work are tabulated with their key parameters in Table 1 and comprise approximately half of the complete REXCESS sample. The objects were selected by right ascension for ease of follow-up observation scheduling, and were observed first.

2.2 X-ray data

The X-ray observations are described in Böhringer et al. (2007). Each cluster was observed using all three detect-

Table 1. Overview of the REXCESS clusters analysed in this paper. CC = cool-core, D = disturbed, M = massive. Abell Name, RA, Dec, z and L_X are from table 3 in Böhringer et al. (2007). r_{500} , CC and D are from table 1 in Pratt et al. (2009); M_{500} was derived from r_{500} and z using the fiducial cosmology. Massive objects are those with M_{500} above the median of the entire REXCESS population, $2.95 \times 10^{14} M_\odot$. ID is used in Figures in Section §3.9.4 to distinguish between the clusters in the sample.

Object	Abell Name	RA	Dec	z	L_X $10^{37} W$	r_{500} kpc	M_{500} $10^{14} M_\odot$	D	CC	M	ID
RXC J0006.0–3443	A2721	00 ^h 06 ^m 03.0 ^s	−34°43'27.0"	0.1147	1.875	1059.3	4.21	D		M	1
RXC J0049.4–2931	S0084	00 ^h 49 ^m 24.0 ^s	−29°31'28.0"	0.1084	1.503	807.8	1.84				2
RXC J0345.7–4112	S0384	03 ^h 45 ^m 45.7 ^s	−41°12'27.0"	0.0603	0.495	688.4	1.04		CC		3
RXC J0547.6–3152	A3364	05 ^h 47 ^m 38.2 ^s	−31°52'31.0"	0.1483	4.667	1133.7	5.53			M	4
RXC J0605.8–3518	A3378	06 ^h 05 ^m 52.8 ^s	−35°18'02.0"	0.1392	4.478	1045.9	4.26		CC	M	5
RXC J0616.8–4748		06 ^h 16 ^m 53.6 ^s	−47°48'18.0"	0.1164	1.597	939.2	2.95	D			6
RXC J0645.4–5413	A3404	06 ^h 45 ^m 29.3 ^s	−54°13'08.0"	0.1644	7.139	1280.0	8.23			M	7
RXC J0821.8+0112	A0653	08 ^h 21 ^m 51.7 ^s	+01°12'42.0"	0.0822	0.673	755.9	1.44				8
RXC J2023.0–2056	S0868	20 ^h 23 ^m 01.6 ^s	−20°56'55.0"	0.0564	0.411	739.5	1.28	D			9
RXC J2048.1–1750	A2328	20 ^h 48 ^m 10.6 ^s	−17°50'38.0"	0.1475	3.215	1078.0	4.75	D		M	A
RXC J2129.8–5048	A3771	21 ^h 29 ^m 51.0 ^s	−50°48'04.0"	0.0796	0.767	900.6	2.42	D			B
RXC J2218.6–3853	A3856	22 ^h 18 ^m 40.2 ^s	−38°53'51.0"	0.1411	3.516	1130.1	5.40	D		M	C
RXC J2234.5–3744	A3888	22 ^h 34 ^m 31.0 ^s	−37°44'06.0"	0.1510	6.363	1283.2	8.06			M	D
RXC J2319.6–7313	A3992	23 ^h 19 ^m 41.8 ^s	−73°13'51.0"	0.0984	0.937	788.7	1.68	D	CC		E

ors (MOS1, MOS2 and PN), and the mean final exposure after cleaning was $(1.4 \pm 0.7) \times 10^4$ s for PN and $(2.1 \pm 0.9) \times 10^4$ s for each of the MOS detectors. All exposures were cleaned from times of high background due to Solar flares and the PN data were corrected for out-of-time events. The mean fraction of exposure time lost to Solar flares was ~ 0.35 for PN and ~ 0.25 for MOS1/2.

Cluster centres were set by finding the density peak of the X-ray image on a scale of $8.2''$ (corresponding to $2 \times$ the PN pixel width), and all radial distances, r , were measured from these centres. r_{500} values are from Pratt et al. (2009) and were found through iteration of the $r_{500} - Y_X$ relation for morphologically relaxed clusters (eq. 1 in Pratt et al. 2009, Arnaud et al. 2007). Electron density profiles are from Croston et al. (2008). They were derived from surface brightness profiles using the non-parametric method of Croston et al. (2006) which performs a direct deprojection based on the assumption of spherical symmetry and a regularisation procedure, and involves a point spread function deconvolution, rather than fitting of a pre-determined gas density distribution to the surface brightness profile.

2.3 Optical data

We used the Wide Field Imager on the MPG/ESO 2.2 m Telescope at La Silla, which is well suited to *XMM-Newton* follow up as it has a similar field of view ($34' \times 33'$). Each set of optical data cover the cluster and a region outside r_{200} which we use for the background assessment. The nominal resolution is $0.238''/\text{pixel}$ and the detector is a 4×2 array of 2 kilopixel \times 4 kilopixel CCDs.

Dithered observations with total exposure times listed in Table 2 were taken in B , V and R bands (ESO filters B/123, V/89, and Rc/162). The raw frames were reduced and co-added using ESO/MVM (ALAMBIC). These were aligned (shifted and rotated), then cropped to exclude regions where any band was missing using the IRAF task `wregister`. SExtractor (version 2.8.6; Bertin & Arnouts 1996) was run on each image and the seeing measured by taking the median full width at half maximum (FWHM) of objects in the unsaturated part of the stellar locus in the

FWHM-Magnitude diagram. Bright but unsaturated isolated point sources, with SExtractor-measured stellarity > 0.965 in all three bands, were confirmed as point sources by eye and used to calculate convolution kernels with which to degrade each set of images to a common seeing for photometry measurements using the IRAF task `psfmatch`. The final seeing was equal to the worst seeing in each set of three images. Star-galaxy separation was performed on the original, non-PSF-matched images.

Examples of stacked, flat-fielded images where stars have been excised are shown in Figures A1, A2, A3 and A4 (online material).

2.4 Subsamples

We use subsamples of the 14 objects in our catalogue, based on their X-ray parameters as given in Table 1. We use the morphological classifications of Pratt et al. (2009, §2.3).

‘Massive’ objects are those with M_{500} above the median of the entire REXCESS population $2.95 \times 10^{14} M_\odot$.

‘Cool-core’ objects have central electron density $h(z)^{-2} n_{e,0} > 4 \times 10^2 \text{ cm}^{-3}$ and have central cooling times $< 10^9 \text{ yr}$ (Pratt et al. 2009, §2.3.1).

‘Disturbed’ objects are classified based on their X-ray centroid shifts w_i ; $w_i = d_i/r_{500}$ for d_i the projected separation between the X-ray peak and centroid in apertures with radii in the range $(0.1 - 1) r_{500}$. If the standard deviation $\langle w_i \rangle$ is above the threshold value $0.01 r_{500}$, the object is classified as disturbed. A detailed description of the determination of this morphological parameter is given in Böhringer et al. (2010, §2.4).

3 ANALYSIS

3.1 Source detection and classification

Source detection and measurement was carried out on PSF-matched images (see Section §2.3) using SExtractor in double image mode, with R as the detection band. Groups of

Table 2. Details of optical observations. Seeing was measured from the images, and the observation date refers to the date when the observations were started. $A_{r>r_{500}}$ and $A_{r>r_{200}}$ are the areas of the regions outside r_{500} and r_{200} which can be used for background estimation.

Object	R_{exp} h	V_{exp} h	B_{exp} h	R_{see} arcsec	V_{see} arcsec	B_{see} arcsec	R_{date}	V_{date}	B_{date}	$A_{r>r_{500}}$ arcmin 2	$A_{r>r_{200}}$ arcmin 2
RXC J0006.0–3443	0.50	0.50	0.75	0.99	0.96	1.05	2008–09–24	2008–09–24	2008–09–24	647.6	416.7
RXC J0049.4–2931	0.50	0.61	1.25	0.99	0.97	1.03	2008–09–23	2008–09–23	2008–09–23	711.4	561.5
RXC J0345.7–4112	0.50	0.50	0.75	0.88	0.97	1.03	2007–11–19	2007–11–19	2007–11–19	602.5	268.0
RXC J0547.6–3152	0.50	1.00	0.50	0.76	1.04	0.95	2000–01–19	2000–01–18	2007–11–14	454.7	315.9
RXC J0605.8–3518	0.50	0.50	1.37	0.76	0.78	0.92	2007–11–27	2007–11–27	2007–11–15	730.6	586.3
RXC J0616.8–4748	0.50	0.50	0.75	0.93	1.02	1.08	2007–11–15	2007–11–15	2007–11–15	740.9	572.4
RXC J0645.4–5413	0.50	0.50	0.75	1.06	1.08	1.19	2000–01–03	2000–01–03	2000–01–03	765.0	606.2
RXC J0821.8+0112	0.83	0.58	0.62	0.95	0.98	1.12	2007–11–15	2007–11–16	2007–11–16	633.1	414.1
RXC J2023.0–2056	0.56	0.67	1.00	0.90	1.01	1.19	2008–07–01	2008–07–01	2008–07–01	462.3	85.8
RXC J2048.1–1750	0.50	0.50	0.75	0.78	0.90	0.99	2008–07–01	2008–07–01	2008–07–03	667.7	526.6
RXC J2129.8–5048	0.50	0.50	0.75	1.21	1.25	1.40	2008–06–30	2008–06–30	2008–06–30	574.0	249.2
RXC J2218.6–3853	0.50	0.50	0.87	1.18	1.15	1.04	2008–09–20	2008–09–20	2008–09–20	744.9	573.4
RXC J2234.5–3744	0.50	0.50	0.75	1.11	1.22	1.41	2008–06–30	2008–06–30	2008–06–30	674.8	477.6
RXC J2319.6–7313	0.44	0.56	0.75	1.07	1.06	1.15	2008–09–21	2008–09–21	2008–09–21	733.2	562.3

≥ 5 pixels with values $\geq 2\sigma$ above the median filtered background per pixel were treated as objects. We used `auto_mag` in SExtractor for magnitude measurements.

Masks were placed on stars:

- magnitude $M_{\text{GSC}} < 14$ in the Guide Star Catalogue 1.2 (Morrison et al. 2001),
- and/or with prominent diffraction or blooming spikes,
- and/or with prominent secondary or higher order reflections.

Initial placement of the masks was performed using a modified version of `automask.sh` from THELI (Erben et al. 2005) and then finely positioned and scaled by hand. Examples are shown in Figure 1. Masking introduces sharp edges which produce spurious detections not present when using unmasked images, so objects which only appeared in masked images were ignored. When a bright object overlaid the edge of a mask, that object was masked individually to avoid blending it with nearby extended objects. Objects from partially exposed regions at the edges of the images – a result of the telescope dithering and frame stacking – were filtered out of the catalogues.

The SExtractor star-galaxy classifier is a neural network trained on a sample of simulated point-source and non-point-source images to return a stellarity s in the range 0–1, where 1 is a point-source and 0 is not. We found that good star-galaxy separation was achieved when the maximum stellarity from all three un-degraded images was considered, and objects with $s > 0.965$ in one of the bands were considered to be stars. Bright objects which were not definitely classified ($s > 0.8$, $R_{\text{AB}} < 21$) were checked by eye. An example stellarity-magnitude diagram with images of some objects is shown in Figure 2. The figure shows good discrimination (a value close to either 1 or 0) of objects which are obviously point-like or extended at bright magnitudes ($R_{\text{AB}} < 20$). At dimmer magnitudes, classifications become increasingly random. Because of the finite thickness of the Galactic disc and a finite upper magnitude on the star population, we expect the number of stars to drop rapidly above the magnitude at which we can no longer properly classify stars. Objects at higher magnitudes which are unclassified in the un-degraded images are always assumed to be galaxies.

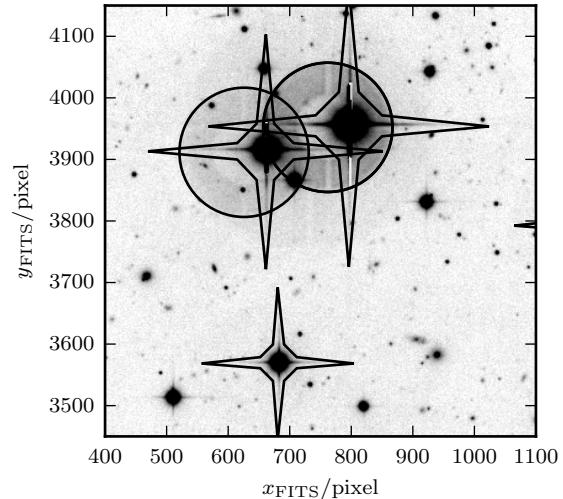


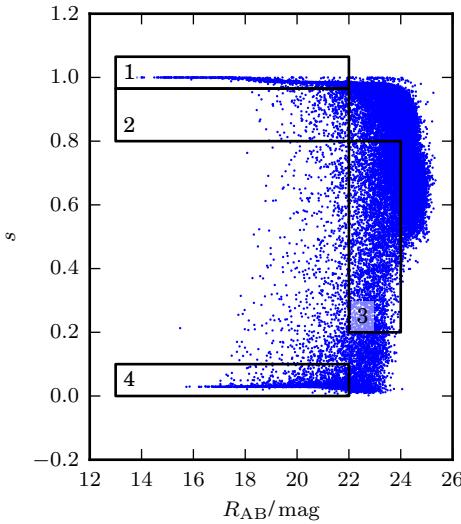
Figure 1. Example masks produced by hand for bright objects. The circles have radius 25''.

By applying the degrading filter, the signal to noise ratio of these objects is increased – the spatially uncorrelated background is suppressed, whereas spatially correlated objects on the scale of the kernel used for degradation are enhanced – so they can be detected.

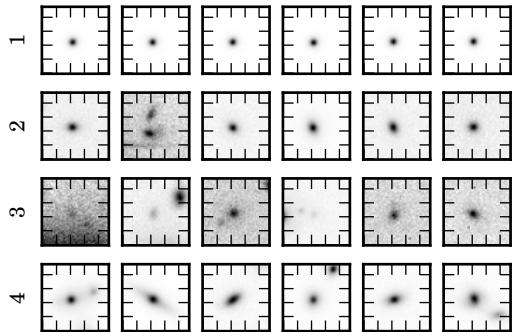
3.2 Magnitude calibration

Magnitudes from SExtractor were converted into AB magnitudes by making an atmospheric correction and a zero point correction. We fixed the B band zero point B_{zero} using Data Release 7 of the AAVSO Photometric All-Sky Survey (APASS DR7) catalogue, which has good coverage of almost all of our fields, and sufficient coverage (>30%) in those fields where coverage was incomplete.

Using the observations and zero points from Ziparo et al. (2012), we generated a calibrated stellar locus. By



(a) Stellarity vs. detection band magnitude.



(b) Examples of the objects contained in the boxes in Figure 2a.

Figure 2. Point source discrimination using SExtractor's object classifier. Any objects with $s < 0.965$ are treated as galaxies. Objects in box 1 are stars, objects in box 2 were checked by eye, objects in box 3 ($R_{AB} > 22$) could not be classified and are assumed to be galaxies, and objects in box 4 are clearly extended. Stars $R_{AB} < 13$ do not appear as they have been masked (note that $M_{GSC} \neq R_{AB}$). These examples come from the images of RXC J0006.0-3443.

minimizing the offset of the stellar locus in each observation set from this calibrated stellar locus, we found colour offsets $\kappa_{B-V} = B_{\text{zero}} - V_{\text{zero}}$ and $\kappa_{V-R} = V_{\text{zero}} - R_{\text{zero}}$. This method is similar to that of High et al. (2009). The resulting zero points are given in Table 3.

No attempt was made to correct for galactic extinction whilst constructing the stellar locus diagram as we found that the assumption that the galactic dust could be modelled as a thin sheet was incorrect, and that bluer stars (brighter and typically further away) tended to be more reddened than redder stars (dimmer and typically closer). Instead, we assumed that the observed stellar locus was independent of position on the sky (at least away from the

Table 3. Zero points for each of the observations. We found B_{zero} using comparison to the APASS catalogue, and then fitted the two colour offsets κ_{B-V} and κ_{V-R} to a stellar locus from the literature in order to constrain V_{zero} and R_{zero} . The large variation in the zero points is due the atmospheric absorption on the observation nights; since the extinction coefficients e_M were not independently determined during observations it was impossible to disentangle extinction from the zero point variation.

Object	R_{zero} mag	V_{zero} mag	B_{zero} mag
RXC J0006.0-3443	24.37 ± 0.02	24.17 ± 0.02	24.70 ± 0.02
RXC J0049.4-2931	23.93 ± 0.03	23.92 ± 0.02	24.52 ± 0.02
RXC J0345.7-4112	24.52 ± 0.05	24.31 ± 0.05	24.87 ± 0.05
RXC J0547.6-3152	24.27 ± 0.02	24.14 ± 0.02	24.44 ± 0.02
RXC J0605.8-3518	24.38 ± 0.02	24.11 ± 0.02	24.61 ± 0.02
RXC J0616.8-4748	24.45 ± 0.02	24.20 ± 0.02	24.71 ± 0.02
RXC J0645.4-5413	24.41 ± 0.02	24.13 ± 0.02	24.61 ± 0.02
RXC J0821.8+0112	24.46 ± 0.03	24.21 ± 0.03	24.73 ± 0.03
RXC J2023.0-2056	24.31 ± 0.03	24.10 ± 0.03	24.65 ± 0.03
RXC J2048.1-1750	24.34 ± 0.02	24.15 ± 0.02	24.71 ± 0.02
RXC J2129.8-5048	24.39 ± 0.02	24.19 ± 0.02	24.76 ± 0.02
RXC J2218.6-3853	24.30 ± 0.02	24.09 ± 0.02	24.65 ± 0.02
RXC J2234.5-3744	24.35 ± 0.02	24.16 ± 0.02	24.69 ± 0.02
RXC J2319.6-7313	24.04 ± 0.03	23.79 ± 0.03	24.11 ± 0.03

galactic plane, where all of our targets are) and that we could cross-calibrate with similar observations.

Conversion of magnitudes and colour gradients to the Johnson system (for comparisons with the literature) was carried out using colour terms from the ESO WFI web page.¹ The conversion between raw magnitudes M_{raw} and Johnson magnitudes M_J is described by

$$\begin{pmatrix} R_{\text{raw}} \\ V_{\text{raw}} \\ B_{\text{raw}} \end{pmatrix} = \begin{bmatrix} 1 + c_R & -c_R & 0 \\ -c_V & 1 + c_V & 0 \\ 0 & -c_B & 1 + c_B \end{bmatrix} \begin{pmatrix} R_J \\ V_J \\ B_J \end{pmatrix} + \begin{pmatrix} Z_R e_R \\ Z_V e_V \\ Z_B e_B \end{pmatrix} - \begin{pmatrix} R_{\text{zero}} \\ V_{\text{zero}} \\ B_{\text{zero}} \end{pmatrix}, \quad (1)$$

for M_{zero} the zero point in band M , c_M the colour term, Z_M the airmass of the observation and e_M the extinction parameter. This equation can be inverted in order to find standard magnitudes given raw magnitudes. The conversion between raw magnitudes and AB magnitudes is described by

$$\begin{pmatrix} R_{\text{AB}} \\ V_{\text{AB}} \\ B_{\text{AB}} \end{pmatrix} = \begin{pmatrix} R_{\text{raw}} \\ V_{\text{raw}} \\ B_{\text{raw}} \end{pmatrix} - \begin{pmatrix} Z_R e_R \\ Z_V e_V \\ Z_B e_B \end{pmatrix} + \begin{pmatrix} O_R \\ O_V \\ O_B \end{pmatrix} + \begin{pmatrix} R_{\text{zero}} \\ V_{\text{zero}} \\ B_{\text{zero}} \end{pmatrix}, \quad (2)$$

for O_M the AB offset for band M . The values of the parameters are given in Table 4, and the AB corrections O_M were taken from the ESO MAG2FLUX tool².

¹ <https://www.eso.org/sci/facilities/lasilla/instruments/wfi/inst/zeropoints.html> [Accessed: 2013-07-24]

² <http://archive.eso.org/mag2flux/>

Table 4. Magnitude conversion parameters. The offsets O_M were taken from the ESO MAG2FLUX tool at <http://archive.eso.org/mag2flux/>.

Band	c_M	e_M	O_M
R	0.0 ± 0	0.070 ± 0.010	$+0.23$
V	-0.13 ± 0.01	0.11 ± 0.01	$+0.14$
B	0.25 ± 0.02	0.22 ± 0.01	-0.07

The results in the rest of this paper are based on AB system magnitudes.

3.3 Luminosity function analysis

3.3.1 Galaxy catalogue completeness from off-target observations

The number counts of field galaxies arise from the summation of luminosity functions at many redshifts, which themselves are influenced by galaxy evolution. We use the number counts histogram to estimate catalogue completeness at different magnitudes, and to compare the relative over- or under-density of galaxies in the off-target regions of our observations to other regions in the sky.

Metcalfe compiled a set of number count measurements³ from Busswell et al. (2004); Frith et al. (2003); Metcalfe et al. (1991); Jones et al. (1991); Metcalfe et al. (2001); McCracken et al. (2000); Metcalfe et al. (1995, 1996, 2005). The dataset has an intrinsic scatter of ~ 0.3 dex, corresponding to a factor of ~ 2 . We use a 5th order polynomial spline fit $\xi_{\text{Metcalfe}}(R)$ as an empirical shape for our field number counts histogram fitting. The number count surface densities S for all of the off-target regions in the sample are plotted in Figure 3, along with ξ_{Metcalfe} .

We assume that the fall-off at the magnitude limit can be described by the logistic function $\xi_{\text{falloff}}(M) = \left(1 + e^{\frac{M - M_{\text{falloff}}}{W_{\text{falloff}}}}\right)^{-1}$. This function was chosen since it goes smoothly from ~ 1 to ~ 0 over a characterisable distance, but we make no claim that it precisely describes the fall-off. The 50% completeness limit is at M_{falloff} in this model.

We fit the function $\Xi = f_g \xi_{\text{Metcalfe}} \xi_{\text{falloff}}$ where f_g is a normalisation factor, to the off-target number counts histogram for each cluster in our sample (measured in region $r > 1.5 r_{500}$), and the results are given in Table 5. We also include the fall-off magnitude as a K-corrected absolute magnitude at the cluster redshift, $R_{\text{AB abs K falloff}}$. The K-corrections are made using the data of Poggianti (1997), assuming that the galaxies are E-galaxies.

The observed galaxy counts were all between $1\times$ and $2\times$ the empirically determined density, consistent with our galaxy clusters occupying denser regions of the cosmic web, and within the expected bounds of the scatter from Metcalfe's galaxy counts dataset. In addition, the shapes of the off-target number counts in Figure 3 do not closely trace the curve expected from the literature, suggesting that the galaxy overdensity of the cluster extends beyond r_{500} .

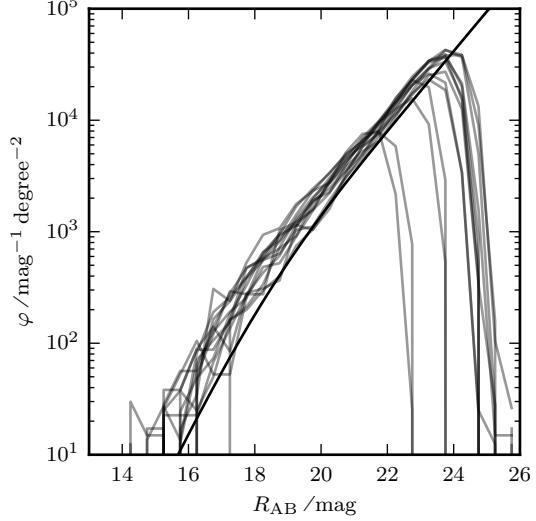


Figure 3. The off-target number count surface densities S for each cluster in the sample are shown in grey, along with the expected number counts from data compiled by Metcalfe in solid black (see Footnote (3)).

Table 6. Schechter function fitting results, valid for the MPG/ESO 2.2 m Telescope WFI filters.

Band	M_* mag	α	χ^2_r
$R_{\text{AB abs K}}$	-22.26 ± 0.17	-1.18 ± 0.04	2.01
$V_{\text{AB abs K}}$	-21.79 ± 0.24	-1.29 ± 0.06	3.43
$B_{\text{AB abs K}}$	-20.87 ± 0.28	-1.22 ± 0.09	3.67

3.3.2 Initial cluster luminosity function analysis

For each cluster, we measured the on-target luminosity function in the region $r < r_{500}$ in the R band, subtracting the off-target number counts histogram measured from the region $r > 1.5 r_{500}$. Each function was normalised by the mean density in $-21 < R < -17$. We truncated each function well below the 50% completeness limit, at $M_{\text{falloff}} - 4W_{\text{falloff}}$ as fitted in the off-target region (see Section §3.3.1). We fitted a Schechter function $\Phi(L) = \phi \left(\frac{L}{L_*}\right)^\alpha \exp\left(-\frac{L}{L_*}\right)$ for L_* the Schechter luminosity (with the corresponding magnitude M_*), α the slope parameter and ϕ a normalisation factor to the mean luminosity function. The function and its fit for the detection band are shown in Figure 4, and the fitting results for all three bands are given in Table 6.

Given the detection band Schechter magnitude R_* , we define three groups of galaxies in each cluster: 'bright' galaxies are those satisfying $(R < R_* + 2.5)$, i.e. $(L/L_* > 0.1)$; 'faint' galaxies satisfy $(R_* + 2.5 < R < R_* + 5)$, i.e. $(0.1 > L/L_* > 0.01)$; and 'dwarf' galaxies satisfy $(R > R_* + 5)$, i.e. $(L/L_* < 0.01)$. Additionally, we define the symbols $R_{*+2.5} = R_* + 2.5$ and $R_{*+5} = R_* + 5$.

The dwarf galaxy population (described in, e.g. Popesso et al. 2006) is not always obvious in our data due to different image depths in different observations. The detection band data are sufficiently deep to reach the faint limit, $R_* + 5$,

³ <http://astro.dur.ac.uk/~nm/pubhtml/counts/counts.html>
Metcalfe, (2010) [Accessed: 13-05-2013]

Table 5. Off-target number counts fit results. $R_{\text{AB falloff}}$ is the detection band falloff magnitude in the observer's magnitude system and $R_{\text{AB abs K falloff}}$ is the corresponding K-corrected absolute magnitude. f_g is the normalisation factor by which the literature number counts function was multiplied.

Object	$R_{\text{AB falloff}}$ mag	$R_{\text{AB abs K falloff}}$ mag	W_{falloff} mag	$f_g R_{\text{AB}}$
RXC J0006.0–3443	24.07 ± 0.03	-14.56 ± 0.03	0.153 ± 0.014	1.49 ± 0.06
RXC J0049.4–2931	23.10 ± 0.03	-15.40 ± 0.03	0.157 ± 0.014	1.33 ± 0.05
RXC J0345.7–4112	24.40 ± 0.04	-12.76 ± 0.04	0.150 ± 0.011	1.16 ± 0.06
RXC J0547.6–3152	23.34 ± 0.03	-15.90 ± 0.03	0.150 ± 0.014	1.39 ± 0.06
RXC J0605.8–3518	23.99 ± 0.03	-15.10 ± 0.03	0.154 ± 0.011	1.53 ± 0.06
RXC J0616.8–4748	23.74 ± 0.02	-14.93 ± 0.02	0.150 ± 0.008	1.37 ± 0.05
RXC J0645.4–5413	23.74 ± 0.03	-15.74 ± 0.03	0.151 ± 0.011	1.17 ± 0.05
RXC J0821.8+0112	24.07 ± 0.03	-13.79 ± 0.03	0.146 ± 0.012	1.27 ± 0.05
RXC J2023.0–2056	24.34 ± 0.03	-12.67 ± 0.03	0.158 ± 0.009	1.26 ± 0.05
RXC J2048.1–1750	24.25 ± 0.02	-14.98 ± 0.02	0.142 ± 0.009	1.46 ± 0.05
RXC J2129.8–5048	24.02 ± 0.04	-13.77 ± 0.04	0.152 ± 0.012	1.10 ± 0.05
RXC J2218.6–3853	22.25 ± 0.03	-16.87 ± 0.03	0.159 ± 0.014	1.19 ± 0.05
RXC J2234.5–3744	24.11 ± 0.03	-15.17 ± 0.03	0.150 ± 0.010	1.39 ± 0.05
RXC J2319.6–7313	21.93 ± 0.05	-16.35 ± 0.05	0.143 ± 0.014	1.71 ± 0.10

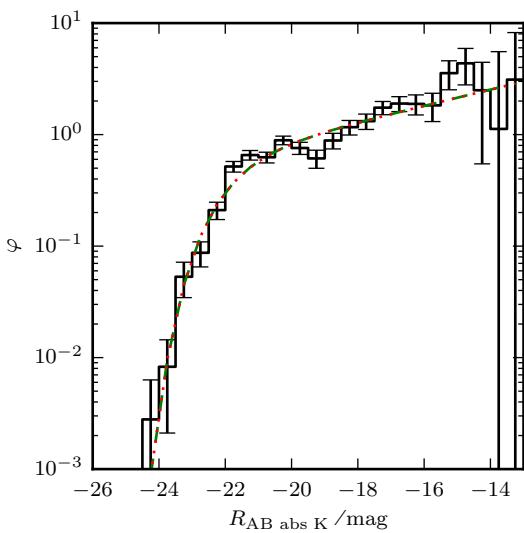


Figure 4. Mean cluster luminosity function in the detection band and best fitting Schechter function model. Before stacking, the off-target number count density was subtracted, and each profile divided by the remaining object count in $-21 < R_{\text{AB abs K}} < -17$.

so in the rest of this paper we use the ‘bright’ and ‘faint’ galaxies, ignoring the dwarfs.

By imposing a magnitude cut at $R_* + 5$, we lose a fraction of the total luminosity in each cluster. By integrating the fitted luminosity functions beyond the cut and extrapolating for very faint objects we can estimate the ratio between the total luminosity in galaxies we observe and the total integrated luminosity in the luminosity function. Luminosities based on the ‘faint’ cut need to be increased by 2.5% in R , 4.3% in V and 3.1% in B .

A more exhaustive assessment of the luminosity functions, as well as total luminosity measurements informed by the count density profiles is given in Section §3.9.

3.4 Catalogue contamination by misidentified stars

We estimate an upper bound on the number of stars at each magnitude in our catalogues by fitting star counts with respect to magnitude at magnitudes where star-galaxy separation is robust, and extrapolating this to higher magnitudes. (These count estimates are upper bounds since the star counts drop off at a faster rate at higher magnitudes.) The number of stars which are expected given the power law, but not seen, are assumed to have been misidentified as galaxies. The contamination fraction K measured in each catalogue at selected magnitudes is given in Table 7.

3.5 Red sequence selection

The red sequence is a line in colour-magnitude space around which elliptical galaxies in clusters tend to scatter (e.g. Bower, Lucey & Ellis 1992; Valentinuzzi et al. 2011). The origin of the red sequence and its relation to the mass-metallicity relation was explored in a seminal paper by Arimoto & Yoshii (1987). The position of the line changes with redshift, and can be used to detect new galaxy clusters and estimate cluster redshifts (e.g. Gladders & Yee 2000). Spiral galaxies in clusters tend to be bluer than the red sequence and migrate on to it as star formation fades. The scatter of field galaxies in colour space is usually much larger than the scatter of the red sequence galaxies and in this study we use this observation to increase the signal to noise ratio of our radial profiles.

We fit a line to the red sequence described by $C_{\text{model}}(M) = g(M - Z) + k$ where C is a colour, g is the gradient, M is a magnitude, and k is the colour at a ‘pivot point’ Z . The distribution of cluster galaxies perpendicular to the red sequence comprises a red sequence of galaxies with a relatively narrow scatter (≤ 0.05 mag in this case) centred on the line, and a blue cloud of galaxies with a larger scatter (~ 0.5 mag) centred some distance below the red sequence. We model this as a distribution of the form

$$\Psi(C_{\text{residual}}) = \psi_r e^{-\frac{(C_{\text{residual}} - o_r)^2}{2\sigma_r^2}} + \psi_b e^{-\frac{(C_{\text{residual}} - o_b)^2}{2\sigma_b^2}}, \quad (3)$$

with $C_{\text{residual}}(C, M) = C - C_{\text{model}}(M)$, where o_r is the offset

Table 7. Contamination fraction for each catalogue measured at the bright limit, the faint limit, and the 50% detection limit.

Object	$K_{R < R_{*+2.5}}$	$K_{R < R_{*+5}}$	$K_{M \text{falloff}}$
RXC J0006.0–3443	-0.00 ± 0.05	0.004 ± 0.014	0.003 ± 0.005
RXC J0049.4–2931	-0.00 ± 0.08	-0.035 ± 0.016	-0.002 ± 0.008
RXC J0345.7–4112	0.00 ± 0.27	-0.01 ± 0.05	-0.005 ± 0.004
RXC J0547.6–3152	-0.00 ± 0.15	0.112 ± 0.027	0.154 ± 0.017
RXC J0605.8–3518	-0.00 ± 0.14	0.268 ± 0.013	0.319 ± 0.004
RXC J0616.8–4748	-0.00 ± 0.21	0.208 ± 0.022	0.270 ± 0.007
RXC J0645.4–5413	0.02 ± 0.09	0.331 ± 0.010	0.365 ± 0.007
RXC J0821.8+0112	0.00 ± 0.18	0.223 ± 0.025	0.324 ± 0.004
RXC J2023.0–2056	0.0 ± 0.5	0.15 ± 0.09	0.474 ± 0.004
RXC J2048.1–1750	0.13 ± 0.05	0.503 ± 0.005	0.5358 ± 0.0033
RXC J2129.8–5048	0.00 ± 0.32	0.05 ± 0.06	0.183 ± 0.005
RXC J2218.6–3853	-0.00 ± 0.15	0.368 ± 0.011	0.277 ± 0.021
RXC J2234.5–3744	-0.02 ± 0.04	-0.057 ± 0.011	0.017 ± 0.006
RXC J2319.6–7313	-0.00 ± 0.20	0.06 ± 0.04	0.222 ± 0.015
Mean	0.01 ± 0.06	0.155 ± 0.010	0.2241 ± 0.0025

of the distribution of red sequence galaxies from the line C_{model} , σ_r the width of the red sequence, and ψ_r the density of the red sequence; o_b , σ_b and ψ_b are equivalent quantities for the blue cloud. For well fitted red sequences, o_r/σ_r should be small ($\ll 1$). We also define

$$w_{\text{rs}} = \frac{C_{\text{residual}} - o_r}{\sigma_r}, \quad (4)$$

which is the scaled displacement of a point from the red sequence in units of the width of the red sequence; galaxies with $-3 < w_{\text{rs}} < 3$ are taken to be on the red sequence and those with $w_{\text{rs}} < -3$ are blue cloud objects.

We consider red sequences in the $(R, B - V) = (M, C)$ colour-magnitude space (in the AB system), and fit to the galaxies satisfying $R < 20$ and $r < r_{500}$.

The fitting procedure was:

- (i) Fit of the straight line C_{model} to the colour-magnitude points, using a least squares method. (On the first iteration, this step was skipped, and we assumed a gradient of -0.044 .)
- (ii) Compute the histogram of C_{residual} for all points within the magnitude limits.
- (iii) Fit of the scatter model Ψ to the histogram.
- (iv) Select points $|w_{\text{rs}}| < 3$ and use these as the input for the straight line fit (i).

Steps (i) to (iv) were repeated enough times that the results stabilized (~ 5 iterations was usually sufficient). In cases where the solutions oscillated, the solution with the narrowest σ_r was selected. The fit results are shown in Figure 5.

To compare our red sequence parameters to those in the literature we refitted g and k in $(R, B - R)$ and $(R, V - R)$ using the same method, before using (1) and (2) to transform g and k into the Johnson-Cousins $(V_J, B_J - V_J)$ colour-magnitude space. K-corrections were made assuming that red sequence objects are elliptical galaxies, using values from Poggianti (1997). The parameters are shown in Table 8. Valentiniuzzi et al. (2011, fig. 3) give values for the K-corrected red sequence normalisation k_{JK} and gradient g_J for 72 clusters in the $(V_J, B_J - V_J)$ colour-magnitude space. The mean values are $\bar{k}_{JK} = 0.87 \pm 0.06$ (at $V_{\text{abs}} = -20$) and $\bar{g}_J = -0.044 \pm 0.009$. These values are in reasonable agreement with our results in Table 8.

The red sequence for RXC J2319.6–7313 is unclear and

achieving a reasonable fit for this object depended on the selection of the solution with the narrowest σ_r . This is the target with the most southerly declination in the REXCESS sample, is only visible from ESO La Silla at relatively high airmass (~ 1.5) and the observation image depth was somewhat lower than for most of the other targets (as shown in Table 5). We suspect that the uncertainties on the measured colours may be underestimated, making the red sequence more difficult to see. Before finding the fitting method described above, we investigated several alternative fitting algorithms in an attempt to get robust fits for RXC J2319.6–7313. Of particular interest was fitting in several bands simultaneously, i.e. iteration of line fitting in $(R, B - R, V - R)$ space with an iterative cut based on perpendicular distance from the line. We found that there is a substantial population of galaxies which are identified as ‘on the red sequence’ using the single band-pair method, but which are excluded from it in the multi-band method. Apart from scatter in the colour measurements, possible reasons for the offsets in the other band pairs are that the galaxies may lie at a substantially different redshift, have substantial dust attenuation or AGN activity, or be influenced by the spread in star formation histories. The improved discrimination of cluster and background galaxies in this case would lead to lower background levels overall and higher signal-to-noise ratios on the radial profiles. However, this method required excellent starting values, and was particularly susceptible to blue objects at fainter magnitudes. For RXC J2319.6–7313, with its broad red sequence which is poorly separated from the blue cloud, the method failed.

There is no significant change in the the red sequence results here – or the subsequent results based on the red sequence selection – for the other clusters when using the other fitting algorithms we investigated.

3.6 Radial density model

We assume a generalised NFW model for the radial density profiles, namely

$$\rho(r) = \frac{\rho_0}{\left(\frac{r}{r_s}\right)^\gamma \left(1 + \left(\frac{r}{r_s}\right)^\alpha\right)^{\frac{\beta-\gamma}{\alpha}}}, \quad (5)$$

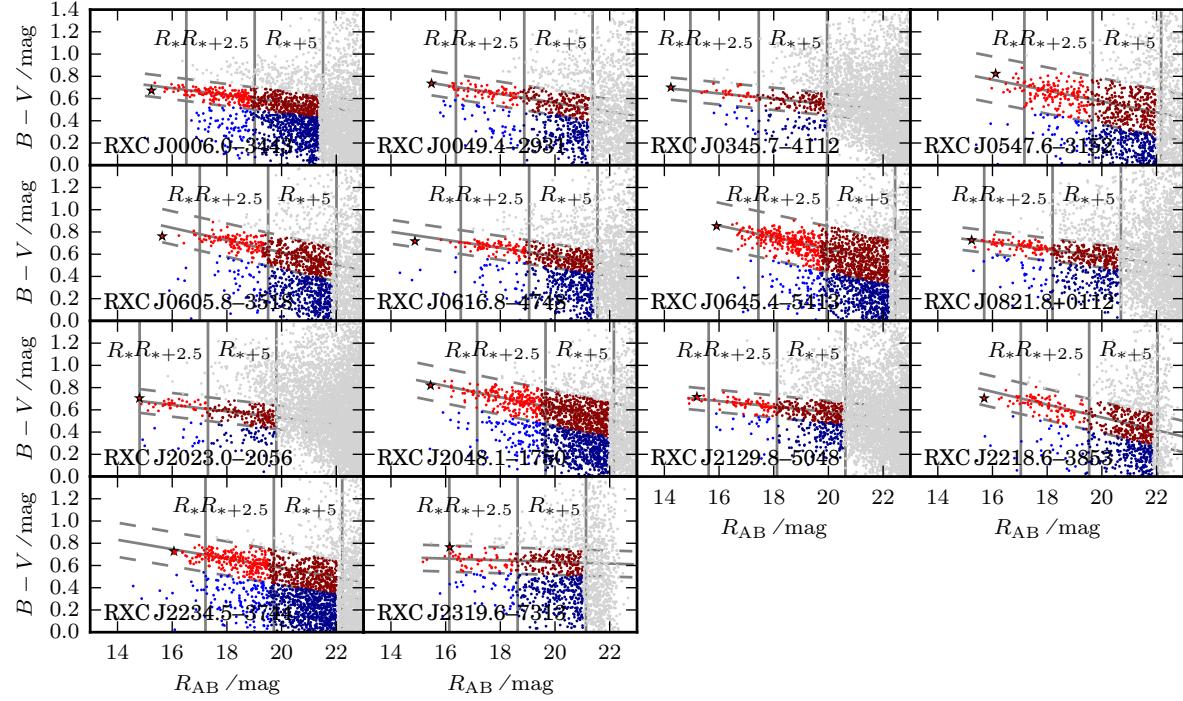


Figure 5. Fitted red sequences for all the clusters in the sample. The red sequence best-fitting line is shown as a solid line, and the dashed lines show $\pm 3w_{rs}$. The vertical lines show the Schechter magnitude, R_* , and the bright and faint magnitude limits, $R_{*+2.5}$ and R_{*+5} respectively. The star denotes the BCG. Objects below the lower dashed line are ‘blue,’ and objects between the dashed lines are ‘on the red sequence.’

Table 8. Red sequence parameters in the Johnson-Cousins colour-magnitude space ($V_J, B_J - V_J$), where g_J is the gradient, and $k_J = V_J, B_J - V_J$ at $V_{abs} = -20$. k_{JK} are compensated for evolution and redshift dependence on colour using values from Poggianti (1997) assuming that the red-sequence comprises of E-galaxies.

Object	g_J	k_J mag	k_{JK} mag
RXC J0006.0-3443	-0.063 ± 0.024	1.12 ± 0.16	0.74 ± 0.16
RXC J0049.4-2931	-0.035 ± 0.031	1.23 ± 0.16	0.87 ± 0.16
RXC J0345.7-4112	-0.053 ± 0.068	0.995 ± 0.155	0.84 ± 0.16
RXC J0547.6-3152	-0.059 ± 0.015	1.18 ± 0.16	0.71 ± 0.16
RXC J0605.8-3518	-0.077 ± 0.017	1.11 ± 0.16	0.66 ± 0.16
RXC J0616.8-4748	-0.045 ± 0.022	0.963 ± 0.150	0.57 ± 0.15
RXC J0645.4-5413	-0.071 ± 0.012	1.15 ± 0.16	0.64 ± 0.16
RXC J0821.8+0112	-0.028 ± 0.010	1.11 ± 0.15	0.85 ± 0.15
RXC J2023.0-2056	-0.038 ± 0.042	1.10 ± 0.15	0.92 ± 0.15
RXC J2048.1-1750	-0.064 ± 0.021	1.03 ± 0.16	0.56 ± 0.16
RXC J2129.8-5048	-0.032 ± 0.009	1.12 ± 0.15	0.86 ± 0.15
RXC J2218.6-3853	-0.055 ± 0.059	1.22 ± 0.19	0.77 ± 0.19
RXC J2234.5-3744	-0.066 ± 0.007	0.997 ± 0.143	0.51 ± 0.14
RXC J2319.6-7313	$+0.007 \pm 0.034$	1.15 ± 0.16	0.83 ± 0.16
Mean	-0.049 ± 0.009	1.11 ± 0.04	0.74 ± 0.04
St. dev.	$+0.022 \pm 0.008$	0.0828 ± 0.0441	0.13 ± 0.04

where ρ_0 is a density normalisation, Δ is the factor by which the halo is overdense with respect to the critical density of the universe at the object redshift, $r_s = 1/c_\Delta$ is a characteristic scale length measured in units of r_Δ , γ is the inner slope, β is the outer slope and $\alpha = 1$. All parameters are calculated in terms of $\Delta = 500$.

There is a strong degeneracy between β and r_s when fitting the generalised NFW profile, so we estimated a value of c_{500} for each cluster using equation (12) from Dolag et al. (2004) to be used in subsequent calculations. The values are shown in Table 9. When analysing stacked profiles, we assume the mean value of c_{500} from all the contributing clusters.

Table 9. Concentration parameters c_Δ with respect to the critical density. The values of $c_{200,m}$ were calculated using equation (12) in Dolag et al. (2004). c_{200} and c_{500} were derived from $c_{200,m}$ assuming our fiducial cosmology.

Object	$c_{200,m}$	c_{200}	c_{500}
RXC J0006.0–3443	7.46 ± 0.07	4.43 ± 0.04	2.907 ± 0.030
RXC J0049.4–2931	8.16 ± 0.06	4.87 ± 0.04	3.217 ± 0.028
RXC J0345.7–4112	9.04 ± 0.07	5.43 ± 0.04	3.609 ± 0.029
RXC J0547.6–3152	7.04 ± 0.07	4.17 ± 0.04	2.724 ± 0.031
RXC J0605.8–3518	7.29 ± 0.07	4.32 ± 0.04	2.833 ± 0.030
RXC J0616.8–4748	7.72 ± 0.06	4.60 ± 0.04	3.024 ± 0.029
RXC J0645.4–5413	6.67 ± 0.07	3.93 ± 0.05	2.560 ± 0.032
RXC J0821.8+0112	8.57 ± 0.06	5.14 ± 0.04	3.400 ± 0.028
RXC J2023.0–2056	8.89 ± 0.07	5.33 ± 0.04	3.539 ± 0.029
RXC J2048.1–1750	7.16 ± 0.07	4.24 ± 0.04	2.775 ± 0.030
RXC J2129.8–5048	8.15 ± 0.07	4.87 ± 0.04	3.213 ± 0.029
RXC J2218.6–3853	7.10 ± 0.07	4.21 ± 0.04	2.751 ± 0.031
RXC J2234.5–3744	6.76 ± 0.07	3.99 ± 0.05	2.600 ± 0.033
RXC J2319.6–7313	8.31 ± 0.06	4.97 ± 0.04	3.284 ± 0.028
Mean	7.737 ± 0.018	4.608 ± 0.011	3.031 ± 0.008
St. dev.	0.785 ± 0.019	0.496 ± 0.012	0.346 ± 0.008

3.7 Brightest cluster galaxy properties and positions

Large cD galaxies in the cluster central region are expected to have a significant impact on the distribution of fainter galaxies, which are less tightly bound and more susceptible to disruption than larger bright galaxies. Their distances from the cluster centres and sizes are given in Table 10.

The BCGs in REXCESS were studied by Haarsma et al. (2010). In this paper we use variable aperture elliptical magnitudes, whereas Haarsma et al. used magnitudes measured in a $12 h^{-1}$ kpc fixed aperture metric radius, and as a consequence the magnitudes we measure here are higher.

3.8 Radial density profiles

By measuring the shape of the radial density profiles of galaxy clusters, we can assess the extent to which galaxies (effectively collisionless particles) trace gas (a collisional fluid) and dark matter (which we assume to be a collisionless fluid) in galaxy clusters of different morphological types and masses. Since the evolutionary history of a galaxy may be quite different if it is on the red-sequence as opposed to in the blue cloud, or bright as opposed to faint, we must consider each sub-population of galaxies (red and bright, red and faint, blue and bright, and blue and faint) separately.

We produced radial surface density profiles S for individual clusters by summing object counts in radial bins around the cluster centres (see Section §2.2 for details on the centring method), with annular bin edges at $(0, 0.1, 0.15, 0.2, 0.25, 0.35, 0.5, 0.7, 1, 1.25, 1.5, 2.5$ and $5) r_{500}$. The number counts were divided by the total exposed area in each annulus to get the surface density.

3.8.1 Count density profile fitting

We fitted the generalised NFW model profile defined in Equation (5) to each of the individual galaxy count density profiles. This measurement is used to constrain the background count density and to provide an estimate of the total galaxy count within a particular radius.

When fitting the model profile to projected quantities like the observed galaxy count density profiles, we integrate $\rho(r)$ numerically along the line of sight, and allow an additional uniform surface density component S_{bgNFW} as background, which is not projected. We fixed $\alpha = \gamma = 1$ because the statistics of the individual profiles were too poor to constrain these parameters.

An additional limit, $\rho(r > r_{\text{cutoff}}) = 0$ is imposed so that the integrals converge and to break the degeneracy between β and S_{bgNFW} . We found that values of S_{bgNFW} were consistent within their uncertainties for $r_{\text{cutoff}} = (2.5, 5$ and $10) r_{500}$ for the red populations which have good statistics, but that the poor statistics of the blue populations led to some cases of negative S_{bgNFW} if $r_{\text{cutoff}} > 2.5 r_{500}$. Whilst there are indications that the cluster extends beyond $2.5 r_{500}$, our data outside that radius are too sparse to make reasonable measurements, so we set $r_{\text{cutoff}} = 2.5 r_{500}$. This limit is also used where we estimate the projected total mass profile within the cluster, and the projected gas density profile.

To generate estimates of the total number of galaxies n_g in each cluster, we integrated the fitted density profiles out to the relevant r_Δ . This was done for each galaxy population (combinations of red/blue and bright/faint) as well as for the combined total population (red and blue, down to the faint limit).

Count density profiles for all of the individual clusters are shown in Figures B1 to B14 (online material) and their best fitting radial density profile parameters are given in Table 11 (full length table is given in Table B1, online material).

3.8.2 Background count density analysis

Before stacking the count density profiles of the clusters, the density of galaxies which are in the same line of sight as the cluster but not physically bound to it must be estimated and subtracted. Having already established that the objects may be embedded in more dense regions of the large scale structure (in Section §3.3.1), we made a number of different estimates of the local background for each observation

Table 10. BCG parameters. $R_{\text{AB abs K}}$ is the absolute magnitude of the BCG and L_R is the corresponding luminosity. r is the distance of the BCG from the X-ray peak. A_c is the ratio of the area of the BCG to $\pi(0.1r_{500})^2$. a_{Kron} is the semi-major axis of the elliptical aperture used to measure the BCG luminosity.

Object	$R_{\text{AB abs K}}$ mag	L_R $10^{11} L_\odot$	r r_{500}	A_c	a_{Kron} kpc
RXC J0006.0–3443	-23.393 ± 0.025	1.65 ± 0.04	0.0033	0.11267 ± 0.00008	55.590 ± 0.028
RXC J0049.4–2931	-23.019 ± 0.026	1.168 ± 0.028	0.0056	0.06321 ± 0.00008	21.180 ± 0.020
RXC J0345.7–4112	-22.92 ± 0.05	1.07 ± 0.05	0.0017	0.099439 ± 0.000031	23.026 ± 0.005
RXC J0547.6–3152	-23.124 ± 0.023	1.287 ± 0.027	0.0241	0.05545 ± 0.00009	28.507 ± 0.034
RXC J0605.8–3518	-23.455 ± 0.022	1.745 ± 0.035	0.0049	0.08959 ± 0.00008	35.869 ± 0.023
RXC J0616.8–4748	-23.791 ± 0.023	2.38 ± 0.05	0.0068	0.14889 ± 0.00010	57.391 ± 0.028
RXC J0645.4–5413	-23.576 ± 0.024	1.95 ± 0.04	0.0095	0.10326 ± 0.00011	53.77 ± 0.04
RXC J0821.8+0112	-22.625 ± 0.025	0.813 ± 0.019	0.0057	0.042928 ± 0.000019	18.431 ± 0.005
RXC J2023.0–2056	-22.204 ± 0.028	0.551 ± 0.014	0.0093	0.064183 ± 0.000027	19.517 ± 0.006
RXC J2048.1–1750	-23.777 ± 0.023	2.35 ± 0.05	0.1729	0.07459 ± 0.00005	30.889 ± 0.016
RXC J2129.8–5048	-22.601 ± 0.024	0.795 ± 0.018	0.1130	0.041114 ± 0.000023	21.526 ± 0.009
RXC J2218.6–3853	-23.424 ± 0.023	1.70 ± 0.04	0.0283	0.06235 ± 0.00013	32.02 ± 0.05
RXC J2234.5–3744	-23.218 ± 0.023	1.404 ± 0.030	0.1475	0.041763 ± 0.000029	29.832 ± 0.014
RXC J2319.6–7313	-22.127 ± 0.031	0.514 ± 0.015	0.0061	0.06545 ± 0.00027	24.68 ± 0.07

Table 11. NFW fitting results for each of the galaxy population filters – bright and faint; red sequence and blue. The full length table is given in Table B1 (online material).

Object	Galaxy filter	β	S_0 r_{500}^{-3}	S_{bgNFW} r_{500}^{-2}
RXC J0006.0–3443	Bright, red	2.7 ± 0.5	49.7 ± 9.0	7.2 ± 2.1
RXC J0049.4–2931	Bright, red	3.4 ± 0.5	59.0 ± 10.9	1.9 ± 0.5
RXC J0345.7–4112	Bright, red	3.2 ± 1.0	12.2 ± 4.5	2.3 ± 0.6
RXC J0547.6–3152	Bright, red	2.67 ± 0.35	50.1 ± 6.8	5.4 ± 1.4
RXC J0605.8–3518	Bright, red	3.2 ± 0.4	55.5 ± 8.8	7.2 ± 0.8
RXC J0616.8–4748	Bright, red	2.58 ± 0.26	30.1 ± 3.4	2.7 ± 0.5
RXC J0645.4–5413	Bright, red	2.74 ± 0.29	96.2 ± 13.0	9.8 ± 1.5
RXC J0821.8+0112	Bright, red	2.5 ± 0.4	25.8 ± 4.0	1.8 ± 0.9

set, with the aim of assessing whether the background level was high because the cluster itself is extended, or due to a uniform surface density of objects across the observation field.

The simplest estimate S_{bgsimple} was found by taking the count density in the region bounded by $r > 1.5r_{500}$. This method is susceptible to contamination by the wings of the galaxy density distribution, including virialised galaxies and structures like infalling subclusters and filaments.

We control for infalling structures which are not azimuthally symmetric by making n independent estimates S_{bgsector} (with standard deviation $\sigma_{S_{\text{bgsector}}}$) of the background level in annular sectors in the same bounded region. If the objects in the sectors are spatially uncorrelated and obey Poisson statistics, we would expect that the combined uncertainty of the n independent samples of the background density, $\alpha_{S_{\text{bgsector}}} = \sigma_{S_{\text{bgsector}}}/\sqrt{n}$, would be the same as the Poissonian value for the complete region, i.e. $\alpha_{S_{\text{bgsector}}} \sim \alpha_{S_{\text{bgsimple}}}$. On the other hand, spatially correlated objects are not drawn from a single Poisson distribution and appear significantly more frequently in some of the sectors, leading to a higher $\alpha_{S_{\text{bgsector}}}$, i.e. we would expect $\alpha_{S_{\text{bgsector}}} > \alpha_{S_{\text{bgsimple}}}$ if local structures are present.

To control for broad wings of the galaxy density distribution, we fitted the NFW model described in Equation (5) - including a constant surface density component S_{bgNFW} - to the individual cluster profiles. S_{bgNFW} is sensitive to uniform density across the field, whereas S_{bgsimple} includes the cluster wings and infalling structures as well.

$S_{\text{bgsimple}}/S_{\text{bgNFW}} > 1$ indicates that S_{bgsimple} is contaminated by the wings of the cluster and overestimates the background level.

The results of these measurements for the red galaxies down to the faint magnitude limit are given in Table 12, and Table 13 includes comprehensive results for all of the galaxy populations used in the radial profiles (the full length table is given in Table C1, online material).

Comparing $\alpha_{S_{\text{bgsector}}}$ and $\alpha_{S_{\text{bgsimple}}}$, we see that 7 of the clusters have $\alpha_{S_{\text{bgsector}}}/\alpha_{S_{\text{bgsimple}}} > 1.5$, consistent with the existence of localised substructures within some of the sectors. We conclude that in half of the sample, filamentary structure or infalling objects contribute to the high background in the cluster outskirts.

Values of > 1 for the ratio $S_{\text{bgsimple}}/S_{\text{bgNFW}}$ are suggestive that, in most cases, S_{bgsimple} is an overestimate contaminated by the wings of the cluster profile. (In the case of RXC J2023.0–2056, S_{bgNFW} is consistent with zero.) Measurements of the remnant luminosity function in this region, once a model of the field galaxy density is removed, are presented in Section 3.9.2.

We can also compare $S_{\text{bgsimple}}/S_{\text{bgNFW}}$ with f_g from Table 5. In RXC J0345.7–4112, RXC J0645.4–5413, RXC J0821.8+0112 and RXC J2129.8–5048, $S_{\text{bgsimple}}/S_{\text{bgNFW}} \geq f_g$, so at least a portion of the overdensity seen in the number counts function is likely due to contamination from the cluster itself, rather than the large scale structure along the line of sight.

The least contaminated estimate of the background

Table 12. Background count density measurements for the red bright and faint galaxy population: simple count density S_{bgsimple} including Poisson uncertainties; standard error measured from sectors $\alpha_{S_{\text{bgsector}}}$; constant density component from an NFW fit S_{bgNFW} . Comprehensive results for red-bright, red-faint, blue-bright and blue-faint galaxy populations are given in Table 13.

Object	S_{bgsimple} arcmin $^{-2}$	$\alpha_{S_{\text{bgsector}}}$ arcmin $^{-2}$	S_{bgNFW} arcmin $^{-2}$	$S_{\text{bgsimple}}/S_{\text{bgNFW}}$	$\alpha_{S_{\text{bgsector}}}/\alpha_{S_{\text{bgsimple}}}$
RXC J0006.0–3443	0.86 ± 0.05	0.04	0.74 ± 0.08	1.17	0.9
RXC J0049.4–2931	0.490 ± 0.029	0.04	0.471 ± 0.019	1.04	1.4
RXC J0345.7–4112	0.124 ± 0.021	0.02	0.090 ± 0.035	1.38	1.1
RXC J0547.6–3152	0.89 ± 0.05	0.08	0.78 ± 0.08	1.15	1.6
RXC J0605.8–3518	1.11 ± 0.04	0.08	1.07 ± 0.06	1.04	1.9
RXC J0616.8–4748	0.73 ± 0.04	0.04	0.67 ± 0.06	1.09	1.1
RXC J0645.4–5413	1.49 ± 0.05	0.13	1.30 ± 0.10	1.15	2.7
RXC J0821.8+0112	0.356 ± 0.029	0.05	0.28 ± 0.05	1.27	1.7
RXC J2023.0–2056	0.13 ± 0.04	0.04	0.05 ± 0.10	2.41	1.0
RXC J2048.1–1750	1.61 ± 0.06	0.10	1.38 ± 0.16	1.17	1.8
RXC J2129.8–5048	0.34 ± 0.04	0.07	0.284 ± 0.031	1.20	1.8
RXC J2218.6–3853	0.80 ± 0.04	0.07	0.81 ± 0.05	0.99	1.8
RXC J2234.5–3744	1.15 ± 0.05	0.05	1.02 ± 0.06	1.13	1.1
RXC J2319.6–7313	0.519 ± 0.030	0.02	0.47 ± 0.05	1.11	0.7

Table 13. Background count density measurements. In the case of the RXC J2023.0–2056 bright blue filter, no objects are detected in the region used for measuring S_{bgsimple} . The full length table is provided in Table C1 (online material).

Object	Galaxy filter	S_{bgsimple} arcmin $^{-2}$	$\alpha_{S_{\text{bgsector}}}$ arcmin $^{-2}$	S_{bgNFW} arcmin $^{-2}$	$S_{\text{bgsimple}}/S_{\text{bgNFW}}$
RXC J0006.0–3443	Bright, red	0.166 ± 0.020	0.02	0.12 ± 0.04	1.34
RXC J0006.0–3443	Faint, red	0.70 ± 0.04	0.04	0.62 ± 0.06	1.12
RXC J0006.0–3443	Bright, blue	0.128 ± 0.017	0.02	0.102 ± 0.029	1.25
RXC J0006.0–3443	Faint, blue	1.14 ± 0.05	0.07	0.66 ± 0.18	1.73
RXC J0049.4–2931	Bright, red	0.064 ± 0.011	0.01	0.051 ± 0.013	1.25
RXC J0049.4–2931	Faint, red	0.427 ± 0.027	0.03	0.411 ± 0.019	1.04
RXC J0049.4–2931	Bright, blue	0.074 ± 0.011	0.01	0.054 ± 0.022	1.38
RXC J0049.4–2931	Faint, blue	0.81 ± 0.04	0.04	0.795 ± 0.024	1.02

galaxy count density appears to be S_{bgNFW} , so we use that to generate background subtracted count density profiles. Whilst relying on a background measurement which is dependent on a prior cluster shape rather than one which is shape independent is not ideal, there is sufficient scope in the NFW model to make a reasonable characterisation of most of the clusters we see.

3.8.3 Comparison profiles and normalisation

With the given count statistics and binning, a deprojection of the count density profiles produces very noisy profiles and therefore comparisons are best made with other projected profiles.

The deprojected electron density profiles of Croston et al. (2008) do not extend to r_{cutoff} (the edge of our galaxy density model) because the cluster X-ray emission becomes too faint to observe, so these were extrapolated using a generalised NFW profile (described in Equation (5)) fit to Croston’s data, assuming c_{500} from Table 9 and allowing β , γ and ρ_0 to vary.

We also wished to compare the galaxy count density profiles with some model of the total mass of the cluster. Since this is dominated by dark matter, we assumed the NFW density profile form described in Equation (5) with $\beta = 3$ and $\alpha = \gamma = 1$, and the relevant c_{500} from Table 9.

The electron and total mass profiles were projected using the same numerical integrator as used for the galaxy count density profile fitting, in the same radial bins and with

the same r_{cutoff} . Typically, the projected electron density profiles are dominated outside of $\sim 0.8 r_{500}$ by extrapolated densities.

Since the electron, total mass and galaxy count density profiles each have different normalisation, we plot $S/\sum_{r < r_{500}} S a$, where a is the total area in the annulus, wherever they are compared.

3.8.4 Stacked profiles

We produce stacked galaxy density profiles for all clusters and each subsample by taking the mean of $S_{\text{norm}} = (S - S_{\text{bgNFW}})/n_{\text{g,r+b}}$ where $n_{\text{g,r+b}}$ is the total galaxy count for the cluster measured from the radial profile of all red and blue galaxies down the faint limit (see Section §3.8.1). The units of S_{norm} and S are r_{500}^{-2} . We produce stacked electron density profiles by taking the mean of $S_{\text{e,norm}} = S_{\text{e}}/\sum_{r < r_{500}} S_{\text{e}} a$, where $S_{\text{e,norm}}$ and S_{e} have units r_{500}^{-2} . Similarly, we produce stacked total mass profiles by taking the mean of $S_{\text{M,norm}} = S_{\text{M}}/\sum_{r < r_{500}} S_{\text{M}} a$, where $S_{\text{M,norm}}$ has units r_{500}^{-2} and S_{M} has units $M_{\odot} r_{500}^{-2}$. The mean profiles for the whole sample are shown in Figure 6.

The bright red profile follows the total mass profile reasonably well. The faint red profile is a little broader and there is a 3σ ($3 \times$ the galaxy count density uncertainty) deficit of faint red galaxies in the central bin. The blue profiles are both substantially broader than the total mass profile. There appears to be suppression of faint blue objects compared to

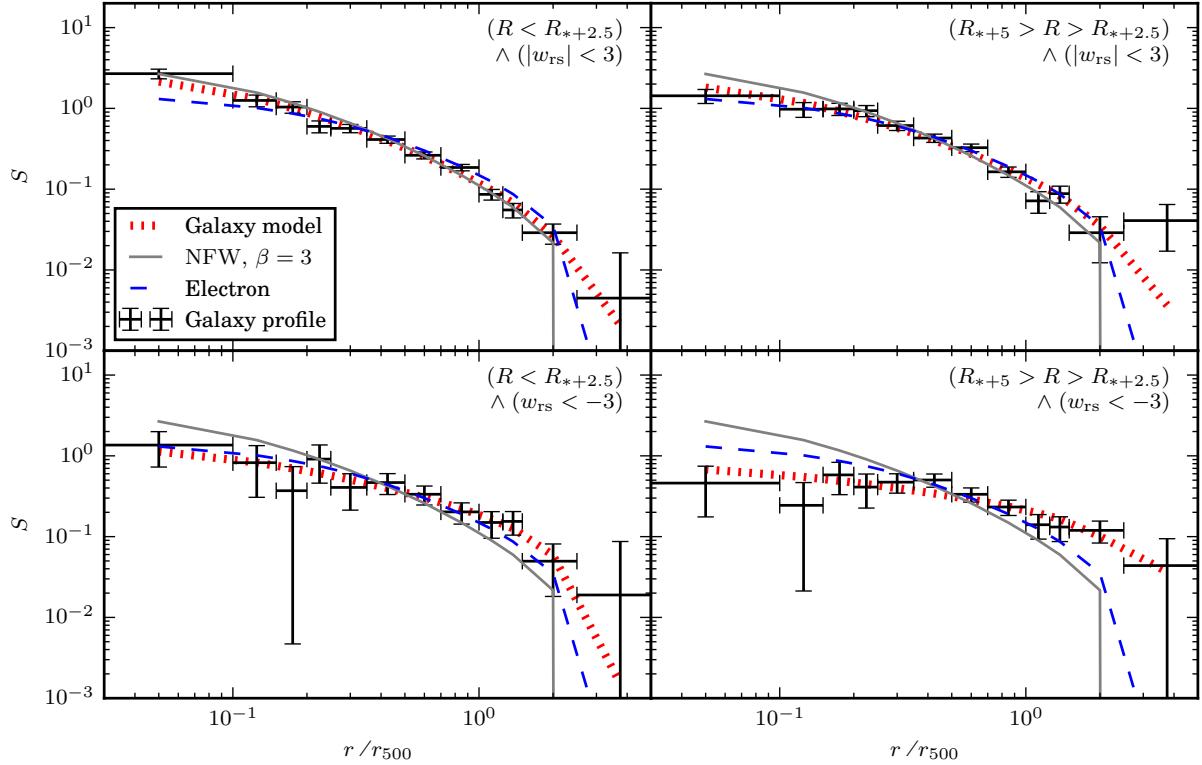


Figure 6. Mean projected radial profile of all of the clusters. Galaxy number density profiles are shown as black points with error bars, with the best fitting NFW model shown as a red dotted line. The projected electron density is shown as a blue dashed line. The NFW profile with parameters ($\alpha = 1, \beta = 3, \gamma = 1$) and c_{500} from Table 9 is shown in grey. The upper panels represent galaxies on the red sequence, and the lower panels include only galaxies bluer than the red sequence. The panels on the left are ‘bright’ and the panels on the right are ‘faint’ galaxies. The radial densities S shown are unitless, having been normalised by the mean S of all of the annuli within r_{500} , such that they overlay each other as closely as possible.

the overall trend which is limited to the region $< 0.15 r_{500}$; with respect to the NFW total mass curve (shown in grey) the deficit is around 5σ . The presence of a cD brightest cluster galaxy in the cluster core could make the detection of faint objects more difficult, but since the BCG occupies a small fraction of the area of the central bin – if indeed it is positioned there – this effect is negligible (see Table 10 for BCG sizes relative to the central bin area, and the distance of the BCG from the X-ray peak). Additionally, we would expect to see a similar effect for the red sequence galaxies, for which there is no evidence.

In Section §2.4 we described subsamples of the REXCESS dataset based on morphological classifications and and cluster total mass. Mean profiles for the massive and low mass subsamples are shown in Figure 7, for the disturbed and regular subsamples in Figure 8, and for the cool-core and non-cool-core subsamples in Figure 9.

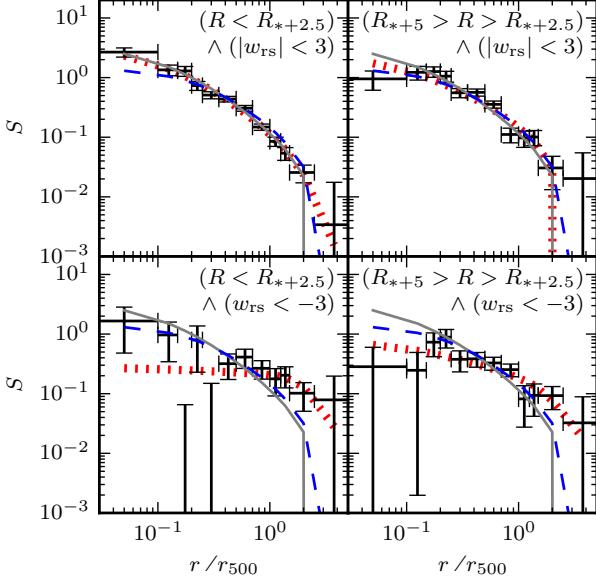
The subsample profiles appear to show that the suppression of faint blue galaxies in the cluster cores is driven by the massive subsample where this effect is marked, and is absent in the low mass subsample (both in Figure 7). The massive subsample also shows suppression of the faint red galaxies in the innermost radial bin ($< 0.1 r_{500}$), not seen in the mean profile for the whole sample. Figure 9 shows that there is even stronger suppression of faint blue galaxies in the cores of the cool-core clusters (only one of which

is classified as massive), and this effect appears in all three cool-core clusters’ individual profiles (see Section §B, online material). Additionally, suppression of bright blue galaxies is noted in the cool-core cluster cores, an effect not seen at all in the stacked profile for the full sample. In the cool-core clusters the red populations appear to be unaffected.

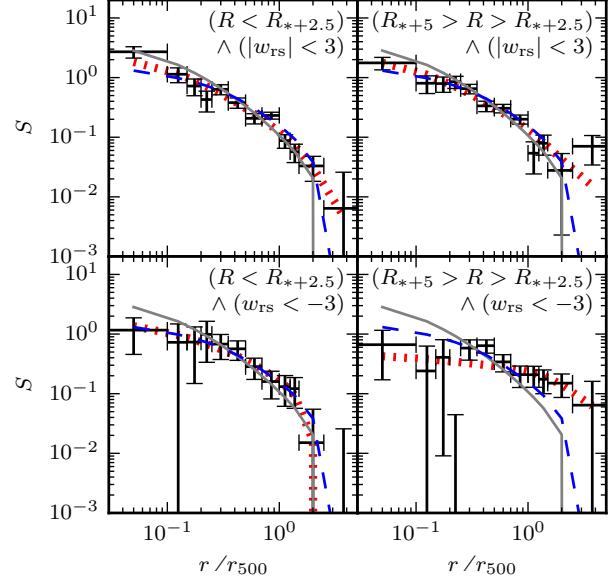
There is some suppression of faint blue galaxies in the centres of the regular clusters, but other than that the profiles for the regular and disturbed clusters appear qualitatively very similar to one another. In particular, we find no evidence from this analysis that there is any substantial difference between the two subsamples which might give a measure of the dynamical state to complement the X-ray based centre shifts parameter used for the disturbed/regular classification (see Section §2.4). The difference which is seen could be statistical noise.

There is strong evidence that the profiles extend at least up to the $2.5 r_{500}$ limit, as the outer bins of the stacked profiles have a significant positive residual even after background subtraction.

We fitted projected generalised NFW models to the stacked galaxy count density profiles using the same method as used for the individual clusters to yield β_g , allowing for a constant density component S_{bgNFW} in case the background subtraction before stacking was incomplete. We include for comparison the mean electron density profile outer slope $\overline{\beta_e}$,

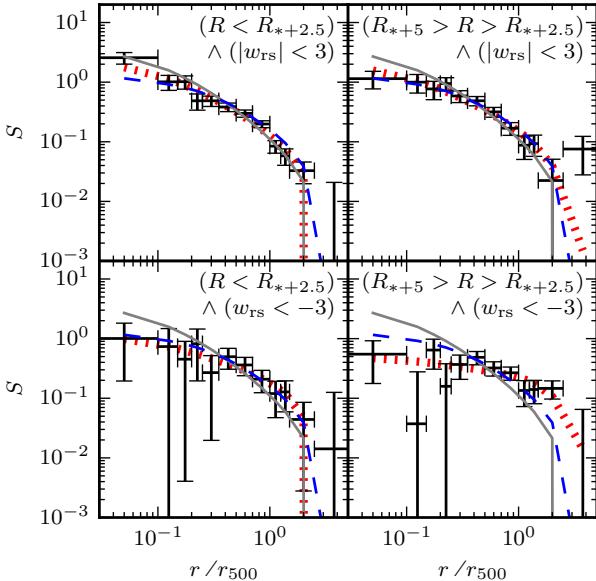


(a) Massive clusters: RXC J0006.0–3443, RXC J0547.6–3152, RXC J0605.8–3518, RXC J0645.4–5413, RXC J2048.1–1750, RXC J2218.6–3853, RXC J2234.5–3744

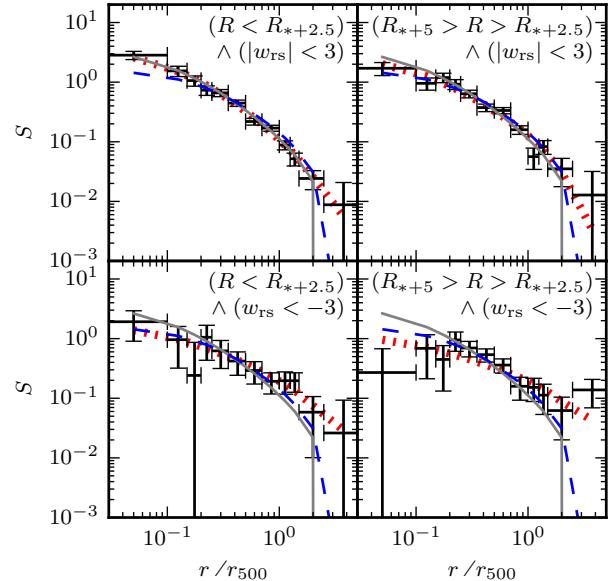


(b) Low mass clusters: RXC J0049.4–2931, RXC J0345.7–4112, RXC J0616.8–4748, RXC J0821.8+0112, RXC J2023.0–2056, RXC J2129.8–5048, RXC J2319.6–7313

Figure 7. Stacked, projected radial number density profiles for clusters above and below the median mass in the population. The lines are the same as described in Figure 6.

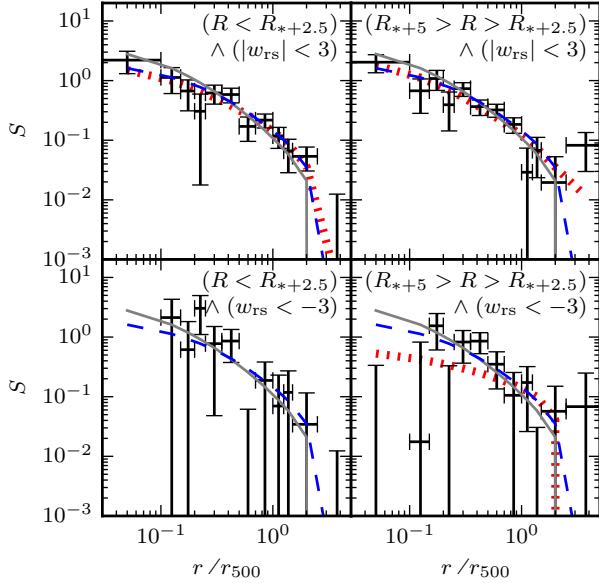


(a) Disturbed clusters: RXC J0006.0–3443, RXC J0616.8–4748, RXC J2023.0–2056, RXC J2048.1–1750, RXC J2129.8–5048, RXC J2218.6–3853, RXC J2319.6–7313

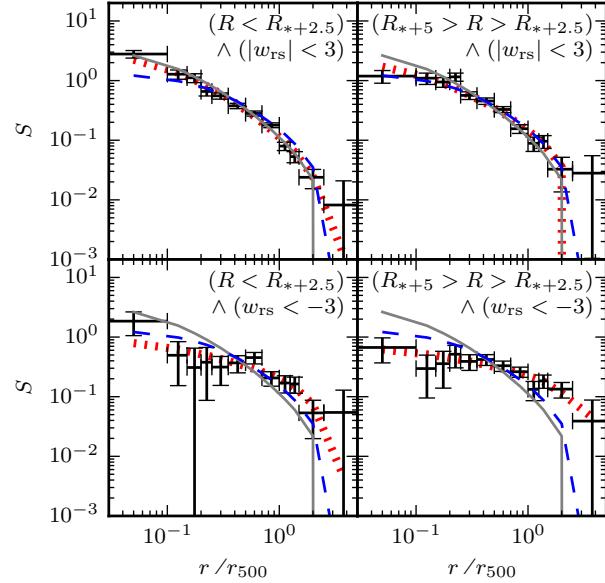


(b) Regular clusters: RXC J0049.4–2931, RXC J0345.7–4112, RXC J0547.6–3152, RXC J0605.8–3518, RXC J0645.4–5413, RXC J0821.8+0112, RXC J2234.5–3744

Figure 8. Stacked, projected radial number density profiles for disturbed and regular clusters. The lines are the same as described in Figure 6.



(a) Cool-core clusters: RXC J0345.7–4112, RXC J0605.8–3518, RXC J2319.6–7313



(b) Non-cool-core clusters: RXC J0006.0–3443, RXC J0049.4–2931, RXC J0547.6–3152, RXC J0616.8–4748, RXC J0645.4–5413, RXC J0821.8+0112, RXC J2023.0–2056, RXC J2048.1–1750, RXC J2129.8–5048, RXC J2218.6–3853, RXC J2234.5–3744

Figure 9. Stacked, projected radial number density profiles for cool-core and non-cool-core clusters. The lines are the same as described in Figure 6.

which is calculated by taking the mean β_e of all the clusters in the subsample. The parameters are tabulated in Table 14 and the fits are shown in Figures 6 to 9.

The best fitting profiles for both bright and faint red sequence galaxies have outer slopes which are flatter than, but nevertheless in rough agreement with $\beta = 3$, the slope of the assumed total mass profile. The bright blue profile is substantially broader than the NFW, and the best fitting has outer slope inconsistent with $\beta = 3$. The faint blue profile is similar, with a best fitting outer slope consistent with the outer slope for the bright blue galaxies but with large uncertainties.

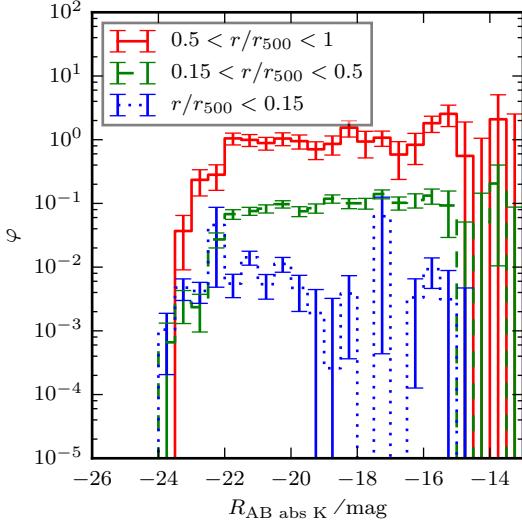
The cumulative fraction of red galaxies for the full sample, and for the high and low mass clusters is shown in Figure 10. These measurements reflect the morphology-density relation for ellipticals and spirals (e.g. Dressler 1984), and our measured blue fraction at the limit of our observations – well within the cluster region of influence – is substantially lower than the field spiral population. Comparing the low mass and massive clusters, we see that outside $0.2 r_{500}$, the red fraction reaches a plateau in the low mass clusters, but in the massive clusters it is still higher than 90% and doesn't reach the same plateau level even at the limit of our observations. Even in low mass clusters, the red fraction approaches 100% in the central regions.

3.9 Luminosity measurements

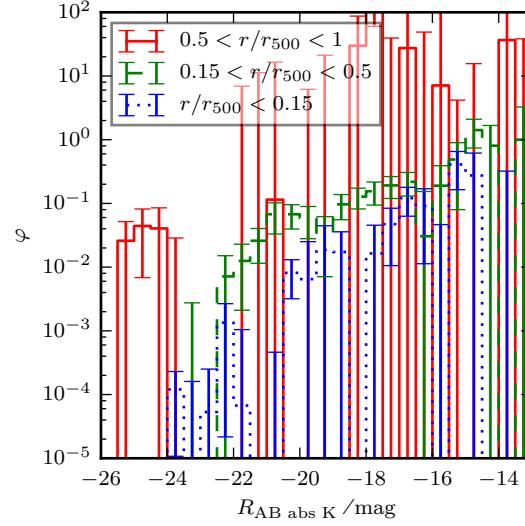
3.9.1 Variation of the cluster luminosity function with radius

Since we see a reduction in the faint galaxy counts in cluster centres, we produced background subtracted luminosity functions for the projected annuli with edges at (0, 0.15, 0.5 and 1.0) r_{500} for the full galaxy population and for the red sequence galaxies. A selection of these luminosity functions are shown in Figure 11. The method of generation, normalisation and stacking is described in Section §3.3.2; the only difference is that we now impose an additional catalogue selection based on the red sequence fit.

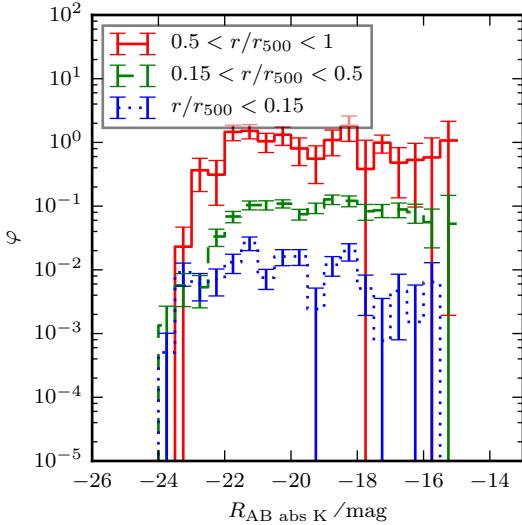
Figure 11 shows that the red sequence luminosity functions outside of $0.15 r_{500}$ are all extremely similar. The inner luminosity functions have a break at around $R_{AB\text{abs}K} = -18$, above which the function drops below the trend. This suppression is largely due to the massive clusters. The uncertainties on the inner luminosity function for the low mass clusters are too large to conclude that there is suppression; within the uncertainties it appears that the faint galaxy count continues the trend seen at brighter magnitudes. We note that the massive clusters are more distant on average, and that the magnitude limit is lower for these observations, but not sufficiently low that it explains the break at $R_{AB\text{abs}K} = -18$. Additionally, the stacking procedure – normalising to a complete part of the luminosity function and ensuring that truncated magnitude bins do not contribute to the mean – should minimize any influence of the completeness limit on the final luminosity function shapes. There is



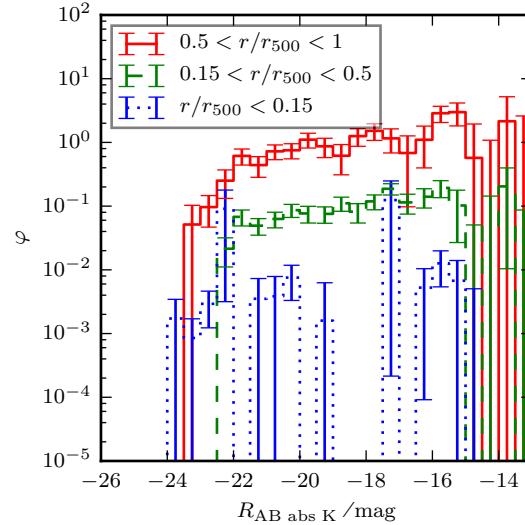
(a) Stacked luminosity functions for all the clusters in the dataset, including red sequence galaxies satisfying $|w_{rs}| < 3$.



(b) Stacked luminosity functions for all the clusters in the dataset, including blue galaxies satisfying $w_{rs} < -3$.



(c) Stacked luminosity functions for massive clusters, including red sequence galaxies satisfying $|w_{rs}| < 3$.



(d) Stacked luminosity functions for low mass clusters, including red sequence galaxies satisfying $|w_{rs}| < 3$.

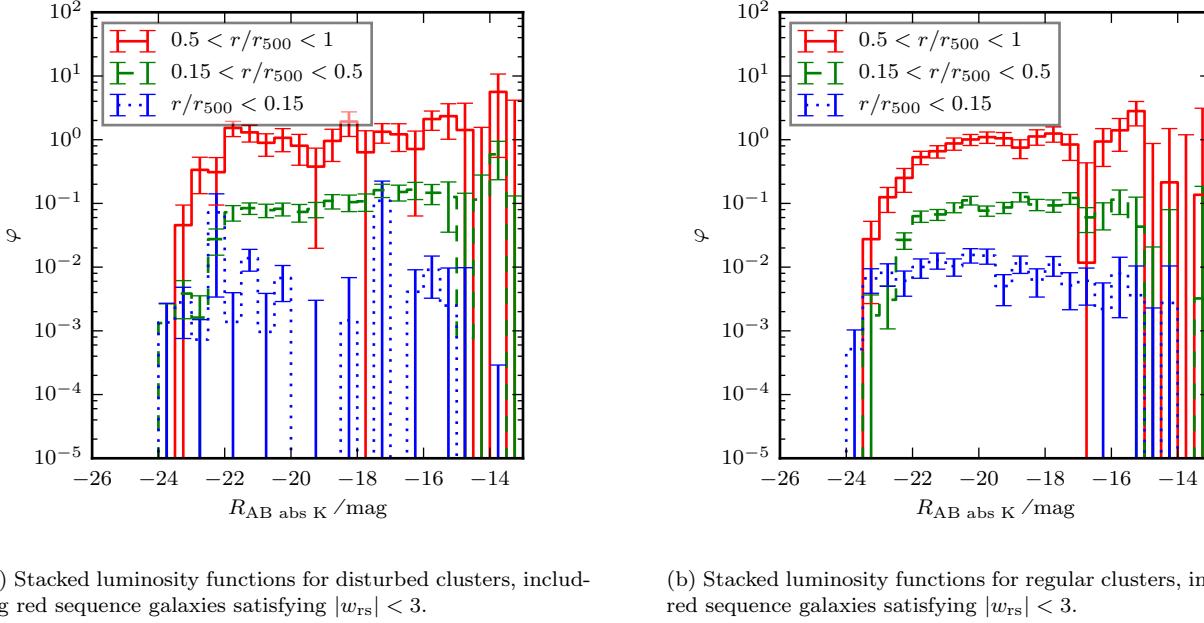
Figure 11. Stacked luminosity functions for the annuli bounded by $(0, 0.15, 0.5 \text{ and } 1.0) r_{500}$. The functions are normalised and then artificially separated by a factor of 10.

some evidence that the massive sample luminosity function is a little flatter than the low mass sample one, but given the size of the uncertainties it is difficult to be certain.

The blue object luminosity functions vary strongly with respect to cluster-centric distance. Figure 11b shows an excess of bright galaxies in the outer cluster regions ($0.5 < r/r_{500} < 1$) which isn't seen at smaller radii, and we found that there was an excess of bright blue galaxies in the off-target region as well. In the two inner regions sampled ($r/r_{500} < 0.15$ and $0.15 < r/r_{500} < 0.5$) there is strong

variation in shape of the luminosity function, away from a simple Schechter function.

There is no evidence of a difference between the luminosity function of disturbed and regular clusters, shown in Figure 12. Any differences which are apparent are consistent with being statistical effects.



(a) Stacked luminosity functions for disturbed clusters, including red sequence galaxies satisfying $|w_{rs}| < 3$.

(b) Stacked luminosity functions for regular clusters, including red sequence galaxies satisfying $|w_{rs}| < 3$.

Figure 12. Stacked luminosity functions for the annuli bounded by $(0, 0.15, 0.5 \text{ and } 1.0) r_{500}$. The functions are normalised and then artificially separated by a factor of 10.

Table 14. Stacked cluster best fitting parameters. ¹No error is quoted where the fitting routine failed to estimate the covariance matrix.

Object	Galaxy filter	β_g	β_e
All clusters	Bright, red	2.78 ± 0.16	2.936 ± 0.026
Massive	Bright, red	2.97 ± 0.16	3.131 ± 0.032
Low mass	Bright, red	2.57 ± 0.30	2.74 ± 0.04
Disturbed	Bright, red	2.53 ± 0.24	2.853 ± 0.034
Regular	Bright, red	3.05 ± 0.13	3.02 ± 0.04
Cool-core	Bright, red	2.3 ± 0.4	2.70 ± 0.06
Non-cool-core	Bright, red	2.86 ± 0.17	3.001 ± 0.028
All clusters	Faint, red	2.51 ± 0.23	2.936 ± 0.026
Massive	Faint, red	2.4 ± 0.4	3.131 ± 0.032
Low mass	Faint, red	2.55 ± 0.32	2.74 ± 0.04
Disturbed	Faint, red	2.29 ± 0.28	2.853 ± 0.034
Regular	Faint, red	2.68 ± 0.24	3.02 ± 0.04
Cool-core	Faint, red	2.6 ± 0.5	2.70 ± 0.06
Non-cool-core	Faint, red	2.40 ± 0.25	3.001 ± 0.028
All clusters	Bright, blue	1.79 ± 0.26	2.936 ± 0.026
Massive	Bright, blue	-0.1 ± 1.6	3.131 ± 0.032
Low mass	Bright, blue	1.84 ± 0.20	2.74 ± 0.04
Disturbed	Bright, blue	1.63 ± 0.34	2.853 ± 0.034
Regular	Bright, blue	2.07 ± 0.34	3.02 ± 0.04
Cool-core	Bright, blue	1.29^1	2.70 ± 0.06
Non-cool-core	Bright, blue	1.4 ± 0.5	3.001 ± 0.028
All clusters	Faint, blue	1.3 ± 0.4	2.936 ± 0.026
Massive	Faint, blue	1.4 ± 0.6	3.131 ± 0.032
Low mass	Faint, blue	0.6 ± 1.2	2.74 ± 0.04
Disturbed	Faint, blue	0.7 ± 0.6	2.853 ± 0.034
Regular	Faint, blue	1.8 ± 0.6	3.02 ± 0.04
Cool-core	Faint, blue	1.2 ± 1.8	2.70 ± 0.06
Non-cool-core	Faint, blue	1.14 ± 0.35	3.001 ± 0.028

3.9.2 Residual cluster luminosity function in the off-target region

Given the evidence of structures in the off-target region in Section §3.8.2 and Section §3.8.4, we re-analysed the luminosity function in the $r_{200} < r$ region to try to find a residual cluster luminosity function, once our assumed field galaxy function was subtracted.

The possible excess of cluster galaxies outside r_{500} means that the normalisation factor f_g found for the assumed field galaxy function ξ_{Metcalfe} (see Section §3.3.1) may be slightly overestimated. However, since the cluster luminosity function is largely invariant with distance from the cluster centre, we can attempt to fit both cluster and field simultaneously for the full image. This should give an improved estimate of f_g , which can be used with ξ_{Metcalfe} as the background.

Assuming values for α and M_* from Table 6⁴ we fitted a combined model $\xi_{\text{falloff}}(\Phi(L) + f_g \xi_{\text{Metcalfe}})$ to the luminosity histogram of each full field, making no magnitude or red-sequence based selections since these may alter the field number counts. The ξ_{Metcalfe} component was subtracted from the count histogram in the off-target region, and the results are shown in Figure 13.

The shape of the residual in Figure 13 appears, in most cases, inconsistent with the shape of the background num-

⁴ α and M_* were fitted to the entire sample. Since the cluster luminosity function is invariant with distance from the cluster centre, the background subtraction performed before the stacking operation in Section §3.3.2 should not bias the shape of the final luminosity function, despite the small residual of cluster galaxies in the region used as the background.

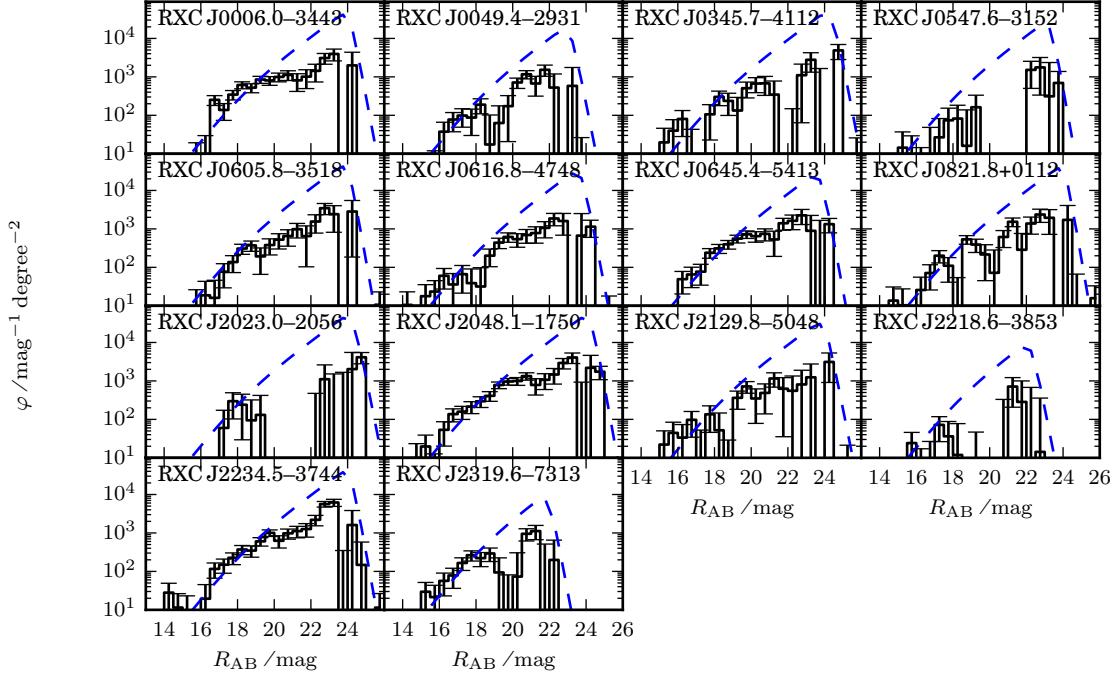


Figure 13. Off-target region ($r_{200} < r$) residual cluster luminosity function. The assumed background model (including the falloff component) is shown as a dashed line for comparison.

ber counts function which is also shown. The residual often resembles the cluster luminosity function. This is consistent with the tentative conclusion drawn in Section §3.8.2, that the cluster does extend some distance outside of r_{200} . Compared with the on-target luminosity functions shown in Section §3.9.1, these residuals have denser faint components, with an upturn at fainter magnitudes similar to the dwarf upturn seen in Popesso et al. (2006), but are also consistent with being due to some remnant field contamination.

3.9.3 Total cluster luminosity

The total cluster luminosity and the related mass-to-light ratio are useful parameters when assessing the efficiency or disruption of star formation in different types of galaxy clusters. Since we are dealing with projected data, a correction needed to be made for the cluster galaxies outside of r_{500} or r_{200} but, when seen in projection, in one of the annular bins.

We considered two populations of galaxies when calculating the total cluster luminosities: $|w_{rs}| < 3$ which includes only galaxies on the red sequence, and $w_{rs} < 3$ which includes both the red sequence and the blue cloud, but excludes objects redder than the red sequence. To ensure that the correction to the total luminosity required due to the magnitude limit was approximately equal for all the clusters in the sample, we considered galaxies satisfying $R < R_* + 5$.

Using the best fitting NFW models – which include a background estimate – for each of the galaxy populations, we assign a weight w which represents the probability that

a galaxy seen in a particular radial bin is within r_Δ . If the total best fitting model count density for a particular radial bin is $S_{\text{total}} = S_{\text{bgNFW}} + S_{\text{NFW},r_{\text{cutoff}}=2.5r_{500}}$ (as described in Section §3.8.1), the weight assigned to each galaxy in that radial bin is $w_\Delta = S_{\text{NFW},r_{\text{cutoff}}=r_\Delta}/S_{\text{total}}$, where S_{NFW} is found by integrating the volume density model ρ in annuli along the line of sight, and setting $\rho = 0$ where $r > r_{\text{cutoff}}$. The total luminosity within r_Δ is then the sum $\sum_i w_\Delta L_i$, and the total count is $\sum_i w_i$ for all galaxies i in the particular population. The major source of uncertainty in this calculation is the uncertainty on w , arising from the uncertainties on the fitting parameters in the model. The BCG is assigned $w = 1$, but other galaxies are not specially treated. Typical values of w are around 0.9 in the innermost radial bins.

Since the radial count density profiles for the bright red, faint red, bright blue and faint blue populations are different, we calculate luminosities for all four subpopulations separately, and then sum the relevant sub-populations to get total red or red plus blue luminosities. In cases where the best fitting model is consistent with there being no overdensity for a particular population and has very large uncertainties on the relevant fit parameters this subpopulation is not included in the final total luminosity. Only the RXC J0345.7-4112 faint blue population is affected by this step.

The total luminosities for each cluster are given in Table 15.

Table 15. Total R band luminosities.

Object	Galaxy filter	L_{500} $10^{12} L_\odot$	L_{200} $10^{12} L_\odot$
RXC J0006.0–3443	Bright and faint, red	1.49 ± 0.16	2.21 ± 0.25
RXC J0006.0–3443	Bright and faint, red and blue	1.78 ± 0.17	2.83 ± 0.28
RXC J0049.4–2931	Bright and faint, red	1.02 ± 0.12	1.30 ± 0.15
RXC J0049.4–2931	Bright and faint, red and blue	1.23 ± 0.16	1.74 ± 0.24
RXC J0345.7–4112	Bright and faint, red	0.266 ± 0.028	0.33 ± 0.04
RXC J0345.7–4112	Bright and faint, red and blue	0.31 ± 0.04	0.38 ± 0.05
RXC J0547.6–3152	Bright and faint, red	2.08 ± 0.17	2.87 ± 0.25
RXC J0547.6–3152	Bright and faint, red and blue	2.20 ± 0.22	3.08 ± 0.31
RXC J0605.8–3518	Bright and faint, red	1.13 ± 0.08	1.46 ± 0.11
RXC J0605.8–3518	Bright and faint, red and blue	1.16 ± 0.09	1.51 ± 0.12
RXC J0616.8–4748	Bright and faint, red	0.96 ± 0.06	1.43 ± 0.10
RXC J0616.8–4748	Bright and faint, red and blue	1.17 ± 0.11	1.79 ± 0.17
RXC J0645.4–5413	Bright and faint, red	3.59 ± 0.26	5.1 ± 0.4
RXC J0645.4–5413	Bright and faint, red and blue	3.61 ± 0.26	5.1 ± 0.4
RXC J0821.8+0112	Bright and faint, red	0.75 ± 0.07	1.18 ± 0.12
RXC J0821.8+0112	Bright and faint, red and blue	0.97 ± 0.09	1.63 ± 0.17
RXC J2023.0–2056	Bright and faint, red	0.49 ± 0.11	0.70 ± 0.18
RXC J2023.0–2056	Bright and faint, red and blue	0.63 ± 0.15	0.88 ± 0.23
RXC J2048.1–1750	Bright and faint, red	2.14 ± 0.23	3.4 ± 0.4
RXC J2048.1–1750	Bright and faint, red and blue	2.63 ± 0.24	4.5 ± 0.4
RXC J2129.8–5048	Bright and faint, red	0.91 ± 0.13	1.14 ± 0.19
RXC J2129.8–5048	Bright and faint, red and blue	0.94 ± 0.13	1.22 ± 0.19
RXC J2218.6–3853	Bright and faint, red	1.04 ± 0.21	1.30 ± 0.25
RXC J2218.6–3853	Bright and faint, red and blue	1.19 ± 0.21	1.55 ± 0.27
RXC J2234.5–3744	Bright and faint, red	3.34 ± 0.13	4.38 ± 0.17
RXC J2234.5–3744	Bright and faint, red and blue	3.81 ± 0.19	5.4 ± 0.4
RXC J2319.6–7313	Bright and faint, red	0.45 ± 0.05	0.77 ± 0.09
RXC J2319.6–7313	Bright and faint, red and blue	0.56 ± 0.07	0.91 ± 0.11

3.9.4 Mass-to-light ratio relation

M_{500} and M_{200} were calculated using r_{500} from Table 1, concentration parameters from Table 9 (to transform between r_{500} and r_{200}) and the fiducial cosmology. We calculated mass-to-light ratios M_Δ/L_Δ for each of the clusters, which are plotted against M_Δ in Figure 14. Using $M_\Delta/L_\Delta = \eta(M_\Delta/M_{\text{pivot}})^\epsilon$ as a model, with $M_{\text{pivot}} = 5 \times 10^{14} M_\odot$, we found best fitting parameters to the mass-to-light vs. mass relation, which are given in Table 16.

Three objects – RXC J0345.7–4112 (cool-core), RXC J00605.8–3518 (cool-core and massive) and RXC J2218.6–3853 (massive and disturbed) – lie slightly above the fitted mass-to-light relationship, but do not significantly affect the fit.

We find a slope ϵ of 0.06 ± 0.10 for the red sequence within r_{200} , and 0.16 ± 0.14 for the red plus blue galaxy population within r_{200} . The increase in slope when the blue luminosity is included compared with the case with just the red sequence luminosity is consistent with a decrease in blue fraction at high masses, already noted in Section §3.8.4 and shown in Figure 10. The increase in the mean luminosity of blue galaxies as cluster mass increases and faint galaxies are disrupted/otherwise suppressed is insufficient to compensate for the decreased blue fraction.

Popesso et al. (2007) measured M_{200}/L_{200} for red sequence objects and quote a slope $\epsilon = 0.18 \pm 0.04$, once projection effects are taken into account. Whilst this result is in fair agreement with our measurements given the uncertainties, both of our best estimates for the red sequence are somewhat flatter.

Sheldon et al. (2009b) quote a logarithmic slope on the

mass-to-light ratio of $\epsilon = 0.33 \pm 0.02$ for objects in the MaxBCG catalogue of galaxy clusters in the i band, a value in fair agreement with our measurement for the red and blue populations, but in this case too, our result is flatter.

The M_{200} range available to both Popesso et al. and Sheldon et al. is $\sim(5 \times 10^{12} - 10^{15}) h^{-1} M_\odot$, substantially larger than the single order of magnitude mass range in REXCESS, lending their analyses greater power to resolve mass dependent effects.

Carlberg et al. (1997) quote an asymptotic value $(289 \pm 50) h M_\odot L_\odot^{-1}$ for the Gunn r band, in excellent agreement with our value of $(3.0 \pm 0.4) \times 10^2 h M_\odot L_\odot^{-1}$ for the red and blue galaxies in the R band, measured at $10^{15} M_\odot$.

4 DISCUSSION

Both the invariance of the cluster luminosity function with respect to radius (outside of cluster centres, i.e. $r > 0.15 r_{500}$) and suppression of faint galaxies in the central regions of galaxy clusters have been noted before (Popesso et al. 2006). Popesso et al. found significant suppression in the late type luminosity function (corresponding to our blue population) for small cluster-centric distances; we find that there is substantial change in the red luminosity function close to the cluster core as well.

The colour-magnitude relation parameters drawn from the WINGS clusters (Valentinuzzi et al. 2011) are quite similar to the values we see here, although the gradient scatter from our sample is twice as large as that from WINGS. That sample is also X-ray selected, but from clusters with lower

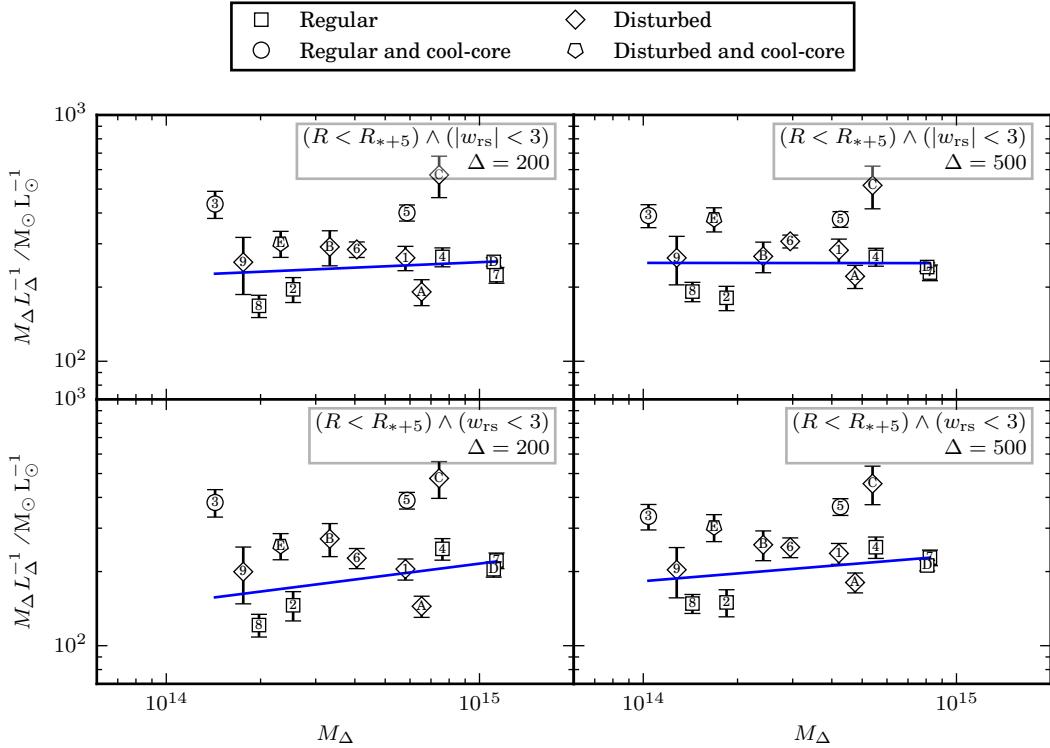


Figure 14. Mass-to-light relations. The marker labels are the IDs given in Table 1. The uncertainties only take into account the luminosities; mass uncertainties have not been considered.

Table 16. Best fitting parameters to the mass-to-light ratio relation $M_\Delta/L_\Delta = \eta (M_\Delta/M_{\text{pivot}})^\epsilon$ where $M_{\text{pivot}} = 5 \times 10^{14} M_\odot$. The values of the $M_\Delta L_\Delta^{-1}$ measured at $10^{14} M_\odot$ and $10^{15} M_\odot$ are corrected for the magnitude cut at $R < R_* + 5$ using the correction factor described in Section §3.3.2. η is not corrected for the magnitude cut.

Galaxy filter	Δ	η $M_\odot L_\odot^{-1}$	ϵ	$M_\Delta L_\Delta^{-1}(10^{14} M_\odot)$ $M_\odot L_\odot^{-1}$	$M_\Delta L_\Delta^{-1}(10^{15} M_\odot)$ $M_\odot L_\odot^{-1}$	$M_\Delta L_\Delta^{-1} h^{-1}(10^{15} M_\odot)$ $M_\odot L_\odot^{-1}$
Bright and faint, red	200	242.9 ± 16.7	0.06 ± 0.10	$(2.2 \pm 0.4) \times 10^2$	$(2.5 \pm 0.2) \times 10^2$	$(3.5 \pm 0.3) \times 10^2$
Bright and faint, red	500	250.4 ± 15.4	-0.00 ± 0.09	$(2.4 \pm 0.4) \times 10^2$	$(2.4 \pm 0.2) \times 10^2$	$(3.5 \pm 0.3) \times 10^2$
Bright and faint, red and blue	200	192.5 ± 18.0	0.16 ± 0.14	$(1.4 \pm 0.4) \times 10^2$	$(2.1 \pm 0.3) \times 10^2$	$(3.0 \pm 0.4) \times 10^2$
Bright and faint, red and blue	500	216.2 ± 15.6	0.10 ± 0.10	$(1.8 \pm 0.3) \times 10^2$	$(2.3 \pm 0.2) \times 10^2$	$(3.2 \pm 0.3) \times 10^2$

redshifts. Whilst it may be the case that there is a tightening of the distribution of red sequence parameters at redshifts approaching $z = 0$, it is difficult to distinguish this effect from the increased measurement uncertainties introduced by increasing numbers of field galaxies in the same region of colour-magnitude space.

Of particular interest to us was any indication that the galaxy density profile of disturbed clusters is also disturbed. Both the slope of the galaxy count density distribution (β_g) and the luminosity functions could have shown differences, but there is no significant evidence of a difference in either of these two properties in the disturbed and regular subsamples. The similarity in the luminosity functions echoes the findings of De Propris et al. (2013) where luminosity functions of collisional and normal clusters in a sample selected by X-ray, optical and weak and strong lensing were studied.

We suggest that two main processes can be invoked to explain the distribution of red and blue, bright and faint galaxies in clusters. Ram pressure stripping occurs as a

galaxy moves with velocity v through the intracluster medium (ICM) with density ρ , and the gas in the galaxy is subjected to pressure $P \propto \rho v^2$ (Gunn & Gott 1972). The pressure ablates cool gas from the halo, slowing star formation and turning blue galaxies redder. This effect should be more pronounced in regions of galaxy clusters with high gas densities, in particular in cool-cores. The galaxy infall velocity is related to the cluster mass M by $v^2 \propto M$, so ram pressure stripping should also be stronger for more massive clusters. Because this process affects bright (as well as faint) galaxies, which dominate the total luminosity of the cluster, it should lead to a decrease in fraction of the cluster luminosity provided by the blue galaxy population as cluster mass increases. As it affects star formation as a whole, it should also lead to decreased overall star formation efficiency in more massive clusters and to a positive slope on the mass-to-light ratio relation measured using just red sequence galaxies.

The second main process, harassment, occurs as weakly bound galaxies interact tidally with more massive objects.

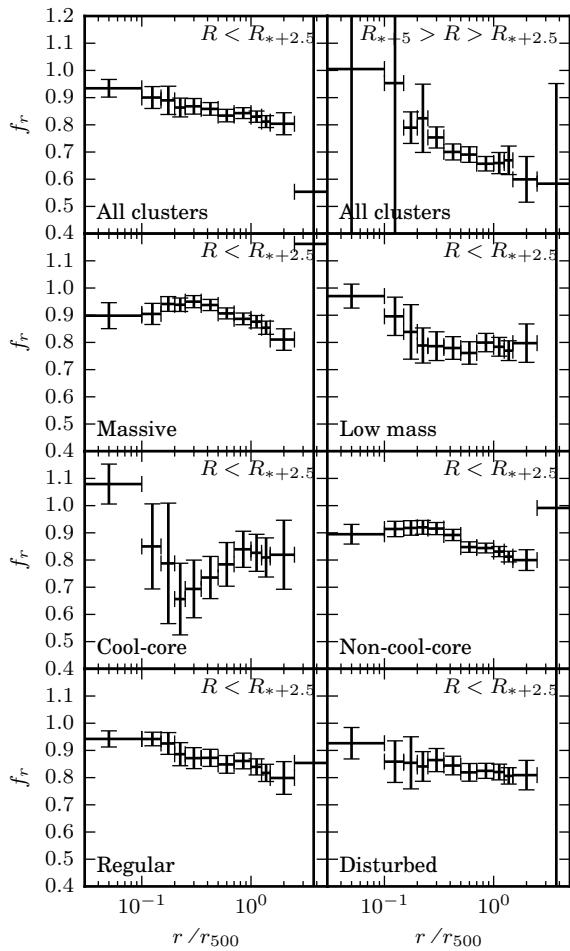


Figure 10. Cumulative fraction of red galaxies. The top two panels show (left) bright and faint galaxies for the whole sample and (right) only bright galaxies for the whole sample. The remaining panels show bright and faint galaxies for the specified subsamples.

Parts of the weakly bound galaxy are stripped away, or the galaxy is completely disrupted. The remnants are a source of intracluster light (ICL). This process is strongest in regions where galaxy count densities and velocities are highest and affects more weakly bound (less massive/lower luminosity) galaxies more. Because the galaxy count densities in the central regions of the clusters are not strongly dependent on mass, this effect is expected to be less mass dependent than ram pressure stripping.

There are several key pieces of evidence we can use to disentangle the two processes. The suppression of faint galaxies independent of the galaxy colour in the densest regions of the galaxy clusters, with the strongest effect in the most massive clusters, suggests harassment – a gravitational process independent of gas density and star formation in the affected galaxy – is important. The steeper mass-to-light ratio relation for the blue plus red galaxies vs. the red sequence alone, as well as decreasing blue galaxy fraction with higher mass, is evidence that ram pressure stripping – a process which primarily affects blue galaxies – is increasingly effective in reducing star formation rates as infall velocities of galaxies rise. From the flatter blue galaxy count density

profiles in all of the clusters, it is clear that the blue galaxy population does not survive long enough to relax into the cluster potential before being stripped of its cold gas and becoming part of the red population. There is some evidence that the suppression of blue galaxies is most pronounced in the regions with the highest gas densities at the centres of cool-core clusters, but given the small sample size we cannot be certain that this is not a statistical anomaly.

The REXCESS sample was selected by X-ray luminosity, ensuring that only clusters which are well evolved and have deep gravitational potential wells with hot, dense ICM are selected. This is in contrast to clusters in optically selected samples which are not always as well evolved, and consequently may not have a sufficiently dense ICM for efficient ram pressure stripping. Böhringer et al. (2004) note that cool-cores in clusters are long-lived, which may allow more time for processes which disrupt galaxies and stop star formation from taking place.

Both the red sequence and red plus blue mass-to-light ratio relation slopes we measure are flatter than in the literature, compared to both X-ray selected samples (Popesso et al. 2007) or optically selected samples (Sheldon et al. 2009a). Given the scatter in the relation and the relatively large uncertainties on the best fitting parameters, as well as the fact that the REXCESS sample contains only clusters spanning one order of magnitude at the highest masses, it is impossible using these data to distinguish between the case where the differences between the slopes measured here and in the literature are purely statistical in nature, or due to different physical processes in the two samples – e.g. stronger ICM effects.

The ICL has not been taken into account in this work, but if the relative density of the ICL in the centres of massive clusters were higher than in low mass clusters, then this would be further evidence for increased harassment. If we assume that 10% of the light of galaxy clusters is ICL (e.g. Zibetti et al. 2005), our mass-to-light ratio normalisations may be overestimated by a factor of ~ 1.1 , leading to a correction of comparable size to the normalisation uncertainties. However, based on the measurements of the BCG sizes and luminosities as compared with Haarsma et al. (2010) described in Section §3.7, it seems likely that a substantial fraction of the intracluster light is included in the BCG luminosity we measure, so the correction may well be smaller.

Gonzalez et al. (2007) and Gonzalez et al. (2013) discuss the reduced efficiency of ICL generation in more massive objects which is coupled with a higher X-ray gas fraction. Zibetti et al. (2005) find that the ICL surface brightness is correlated with BCG luminosity, but that the total fraction of light contributed by the ICL is almost independent of cluster richness and BCG luminosity. Given the open discussion on the ICL light fraction as a function of cluster mass, it is too premature to include the effect of the ICL in the mass-to-light ratio in our results.

5 SUMMARY AND CONCLUSIONS

We have used a sample of 14 galaxy clusters from the REXCESS survey to investigate radial density profiles of galaxies and intra-cluster medium.

- The red galaxy density traces the dark matter dens-

ity closely outside of the cluster centres (in the region $r > 0.15 r_{500}$). The best fitting NFW model outer-slopes β_g are roughly consistent with $\beta_g = 3$, with a best estimate $\beta_g = 2.78 \pm 0.16$, fitted to the stacked bright red sequence galaxy density profile of all the clusters.

- The blue sequence count density profile slopes are substantially shallower than the $\beta = 3$ total mass model, with a best estimate $\beta_g = 1.79 \pm 0.26$, fitted to the stacked bright blue galaxy density profile of all the clusters.

- The mean outer slope for the gas density profiles of the full sample is $\beta_e = 2.936 \pm 0.026$. Within the cluster centres the gas and dark matter profiles tend to diverge.

- We find that faint blue galaxies are suppressed in the centres of massive and regular clusters. Faint red galaxies are also suppressed in the centres of massive clusters. Both bright and faint blue galaxies are heavily suppressed in the centres of cool-core clusters, but the faint red galaxies are unaffected. This is consistent with the idea that the suppression of star formation is driven by ram pressure stripping of gas from galaxies, but that wholesale disruption of galaxies is caused by galaxy interactions in regions with high galaxy densities.

- Our measurement of the logarithmic slope ϵ of the galaxy cluster mass-to-light relation within r_{200} of 0.16 ± 0.14 for all galaxies, measured in the R band, is in fair agreement with $\epsilon = 0.33 \pm 0.02$ from Sheldon et al. (2009b), measured in the i band. Our measurement of the mass to light ratio normalisation of $(3.0 \pm 0.4) \times 10^2 h M_\odot L_\odot^{-1}$ (evaluated at $10^{15} M_\odot$) in the R band is in excellent agreement with Carlberg et al. (1997) measured in the Gunn r band.

- There is no evidence of any difference in the galaxy count density profiles when comparing clusters classified as having disturbed X-ray morphology with those which are regular.

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REFERENCES

- Arimoto N., Yoshii Y., 1987, A&A, 173, 23
 Arnaud M., Pointecouteau E., Pratt G. W., 2007, A&A, 474, L37
 Astropy Collaboration et al., 2013, A&A, 558, A33
 Bertin E., Arnouts S., 1996, A&AS, 117, 393
 Böhringer H., Matsushita K., Churazov E., Finoguenov A., Ikebe Y., 2004, A&A, 416, L21
 Böhringer H. et al., 2010, A&A, 514, A32
 Böhringer H. et al., 2007, A&A, 469, 363
 Boselli A., Gavazzi G., 2006, PASP, 118, 517
 Bower R. G., Benson A. J., Malbon R., Helly J. C., Frenk C. S., Baugh C. M., Cole S., Lacey C. G., 2006, MNRAS, 370, 645
 Bower R. G., Lucey J. R., Ellis R. S., 1992, MNRAS, 254, 601
 Busswell G. S., Shanks T., Frith W. J., Outram P. J., Metcalfe N., Fong R., 2004, MNRAS, 354, 991
 Butcher H., Oemler Jr. A., 1984, ApJ, 285, 426
 Carlberg R. G., Yee H. K. C., Ellingson E., 1997, ApJ, 478, 462
 Chon G., Böhringer H., Nowak N., 2013, MNRAS, 429, 3272
 Croston J. H., Arnaud M., Pointecouteau E., Pratt G. W., 2006, A&A, 459, 1007
 Croston J. H. et al., 2008, A&A, 487, 431
 De Propris R., Phillipps S., Bremer M. N., 2013, MNRAS, 434, 3469
 Dolag K., Bartelmann M., Perrotta F., Baccigalupi C., Moccardini L., Meneghetti M., Tormen G., 2004, A&A, 416, 853
 Dressler A., 1984, ARA&A, 22, 185
 Dressler A., Oemler Jr. A., Butcher H. R., Gunn J. E., 1994, ApJ, 430, 107
 Erben T. et al., 2005, Astronomische Nachrichten, 326, 432
 Fabian A. C., 1994, ARA&A, 32, 277
 Fabian A. C., 2012, ARA&A, 50, 455
 Farouki R., Shapiro S. L., 1981, ApJ, 243, 32
 Frith W. J., Busswell G. S., Fong R., Metcalfe N., Shanks T., 2003, MNRAS, 345, 1049
 Gladders M. D., Yee H. K. C., 2000, AJ, 120, 2148
 Gonzalez A. H., Sivanandam S., Zabludoff A. I., Zaritsky D., 2013, ApJ, 778, 14
 Gonzalez A. H., Zaritsky D., Zabludoff A. I., 2007, ApJ, 666, 147
 Gunn J. E., Gott III J. R., 1972, ApJ, 176, 1
 Haarsma D. B. et al., 2010, ApJ, 713, 1037
 High F. W., Stubbs C. W., Rest A., Stalder B., Challis P., 2009, AJ, 138, 110
 Hunter J. D., 2007, Computing In Science & Engineering, 9, 90
 Jones L. R., Fong R., Shanks T., Ellis R. S., Peterson B. A., 1991, MNRAS, 249, 481
 Köhlinger F., Schmidt R. W., 2014, MNRAS, 437, 1858
 Kravtsov A. V., Borgani S., 2012, Annual Review of Astronomy and Astrophysics, 50, 353
 Larson R. B., Tinsley B. M., Caldwell C. N., 1980, ApJ, 237, 692
 Lin Y.-T., Mohr J. J., Stanford S. A., 2003, ApJ, 591, 749
 McCracken H. J., Metcalfe N., Shanks T., Campos A., Gardner J. P., Fong R., 2000, MNRAS, 311, 707

- Metcalfe N., Shanks T., Campos A., Fong R., Gardner J. P., 1996, *Nature*, 383, 236
- Metcalfe N., Shanks T., Campos A., McCracken H. J., Fong R., 2001, *MNRAS*, 323, 795
- Metcalfe N., Shanks T., Fong R., Jones L. R., 1991, *MNRAS*, 249, 498
- Metcalfe N., Shanks T., Fong R., Roche N., 1995, *MNRAS*, 273, 257
- Metcalfe N., Shanks T., Weilbacher P. M., McCracken H. J., Fong R., Thompson D., 2005, ArXiv Astrophysics e-prints
- Moore B., Katz N., Lake G., Dressler A., Oemler A., 1996, *Nature*, 379, 613
- Moore B., Lake G., Katz N., 1998, *ApJ*, 495, 139
- Morrison J. E., Röser S., McLean B., Buccarelli B., Lasker B., 2001, *AJ*, 121, 1752
- Oemler Jr. A., Dressler A., Butcher H. R., 1997, *ApJ*, 474, 561
- Ostriker J. P., Hausman M. A., 1977, *ApJ*, 217, L125
- Poggianti B. M., 1997, *A&AS*, 122, 399
- Popesso P., Biviano A., Böhringer H., Romaniello M., 2006, *A&A*, 445, 29
- Popesso P., Biviano A., Böhringer H., Romaniello M., 2007, *A&A*, 464, 451
- Popesso P., Böhringer H., Brinkmann J., Voges W., York D. G., 2004, *A&A*, 423, 449
- Pratt G. W., Croston J. H., Arnaud M., Böhringer H., 2009, *A&A*, 498, 361
- Reiprich T. H., Basu K., Ettori S., Israel H., Lovisari L., Molendi S., Pointecouteau E., Roncarelli M., 2013, *Space Sci. Rev.*, 177, 195
- Sheldon E. S. et al., 2009a, *ApJ*, 703, 2232
- Sheldon E. S. et al., 2009b, *ApJ*, 703, 2217
- Valentinuzzi T. et al., 2011, *A&A*, 536, A34
- Zibetti S., White S. D. M., Schneider D. P., Brinkmann J., 2005, *MNRAS*, 358, 949
- Ziparo F., Braglia F. G., Pierini D., Finoguenov A., Böhringer H., Bongiorno A., 2012, *MNRAS*, 420, 2480

Supplementary material (online)

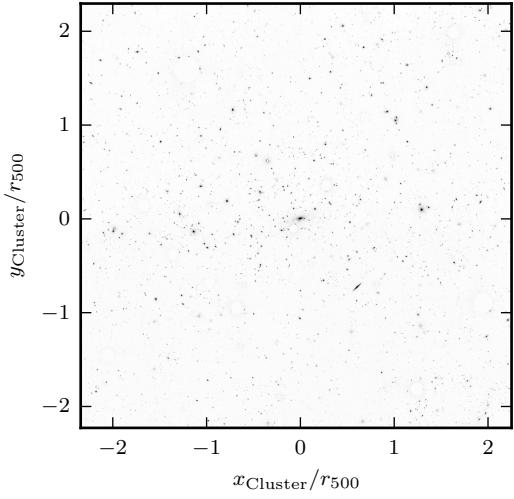


Figure A1. RXC J0006.0–3443 in the R band. Stars have been excised from this image.

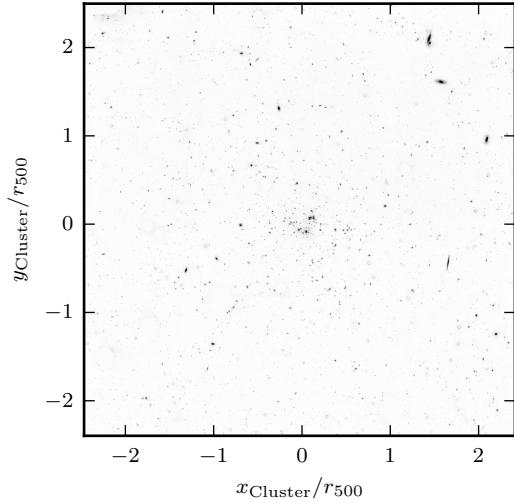


Figure A3. RXC J2234.5–3744 in the R band. Stars have been excised from this image.

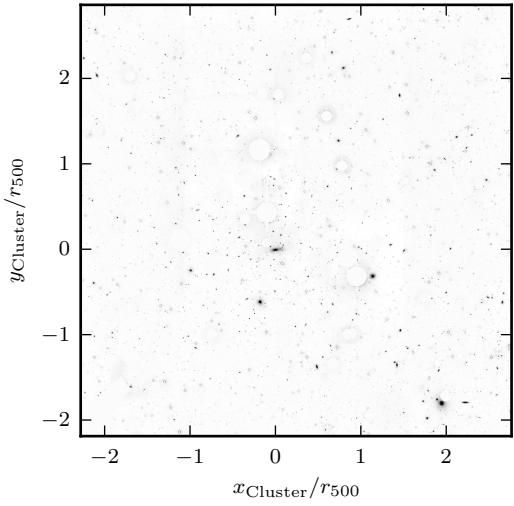


Figure A2. RXC J0616.8–4748 in the R band. Stars have been excised from this image.

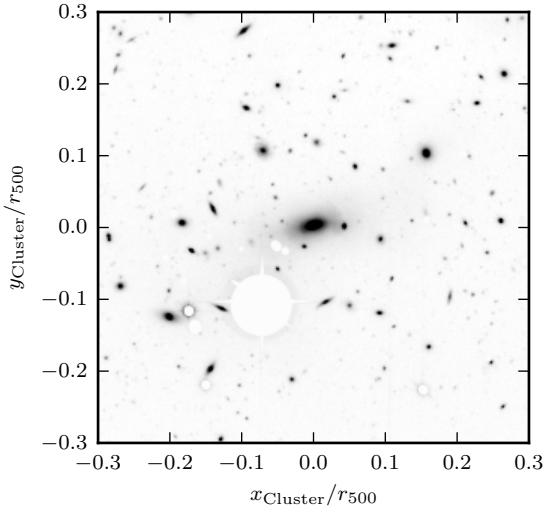


Figure A4. The centre of RXC J0006.0–3443 in the R band. Stars have been excised from this image.

APPENDIX A: ADDITIONAL FIGURES

Figure A1, Figure A2, Figure A3 and Figure A4 show R band images of a selection of our targets, where the stars have been excised from the images.

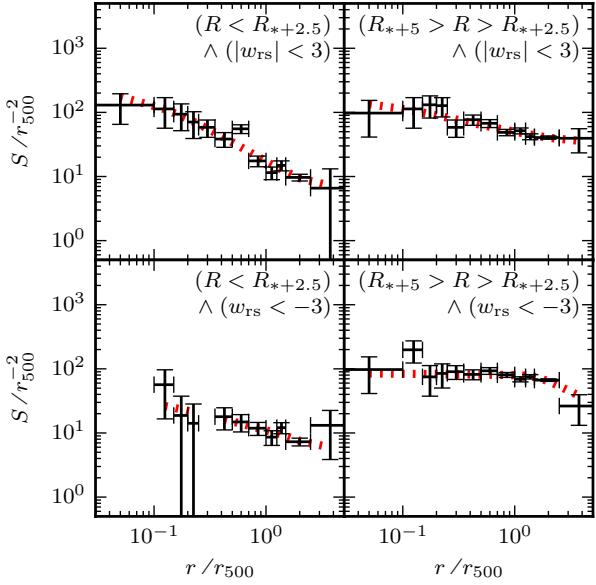


Figure B1. Radial density profiles for RXC J0006.0–3443. The points with uncertainties represent the galaxy count density profile, normalised by r_{500}^2 , and the red dashed line is the best fitting model with parameters given in Table B1.

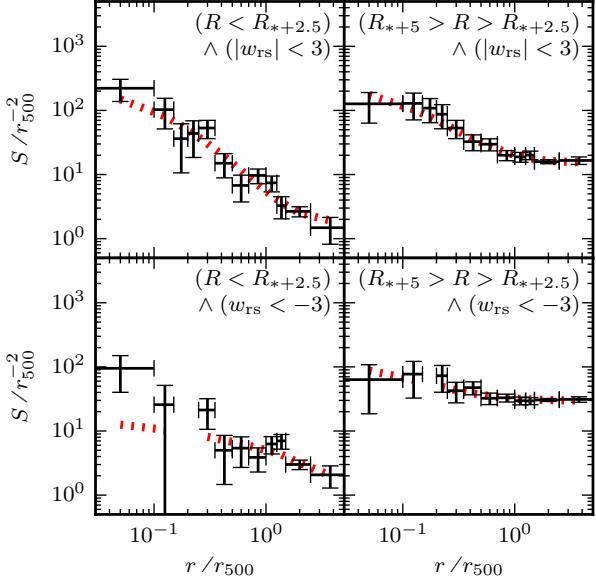


Figure B2. Radial density profiles for RXC J0049.4–2931. The lines are the same as described in Figure B1.

APPENDIX B: INDIVIDUAL CLUSTER RADIAL PROFILES

Figures B1 to B14 show radial count density profiles and best fitting models, before background subtraction, of individual clusters in the REXCESS sample. The best fitting radial profile parameters for each galaxy population in individual clusters in the REXCESS sample are given in Table B1.

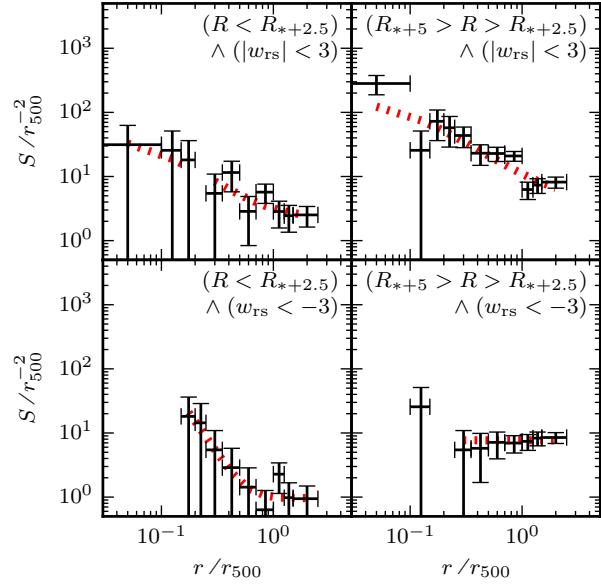


Figure B3. Radial density profiles for RXC J0345.7–4112. The lines are the same as described in Figure B1.

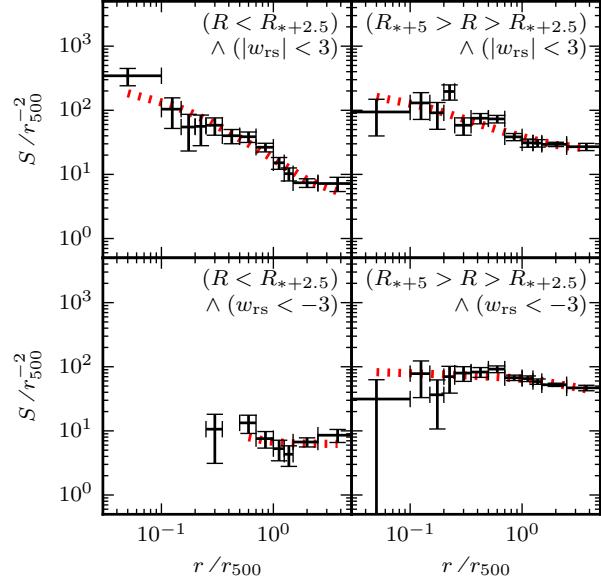


Figure B4. Radial density profiles for RXC J0547.6–3152. The lines are the same as described in Figure B1.

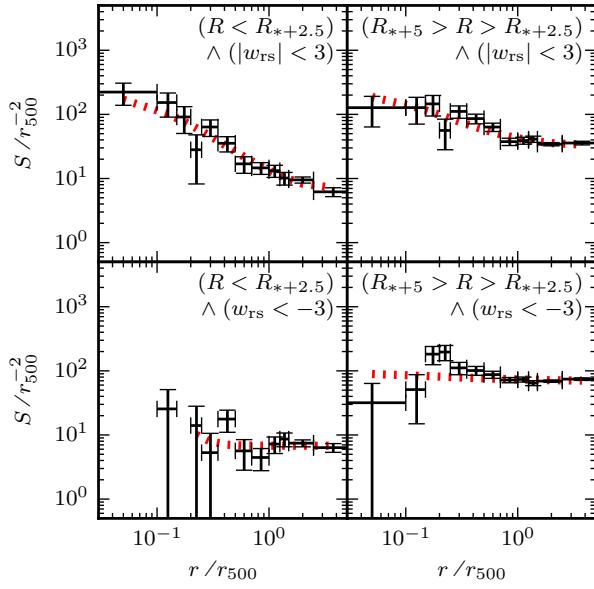


Figure B5. Radial density profiles for RXC J0605.8–3518. The lines are the same as described in Figure B1.

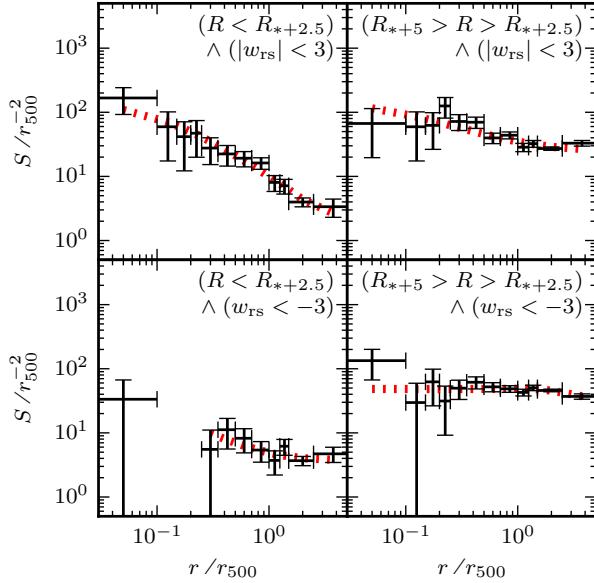


Figure B6. Radial density profiles for RXC J0616.8–4748. The lines are the same as described in Figure B1.

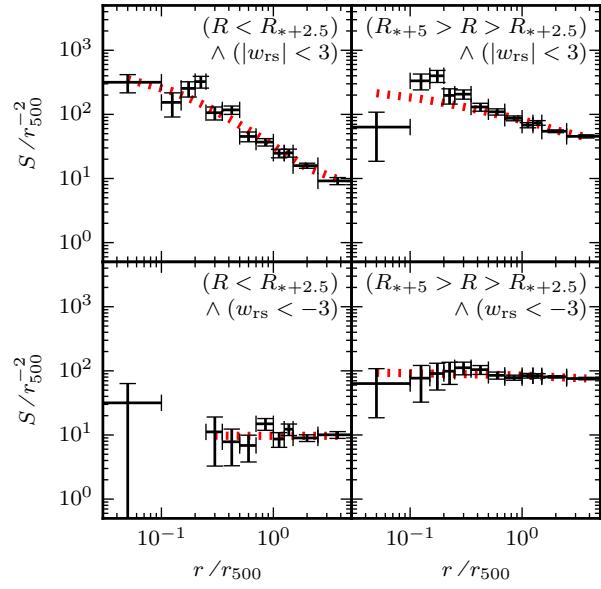


Figure B7. Radial density profiles for RXC J0645.4–5413. The lines are the same as described in Figure B1.

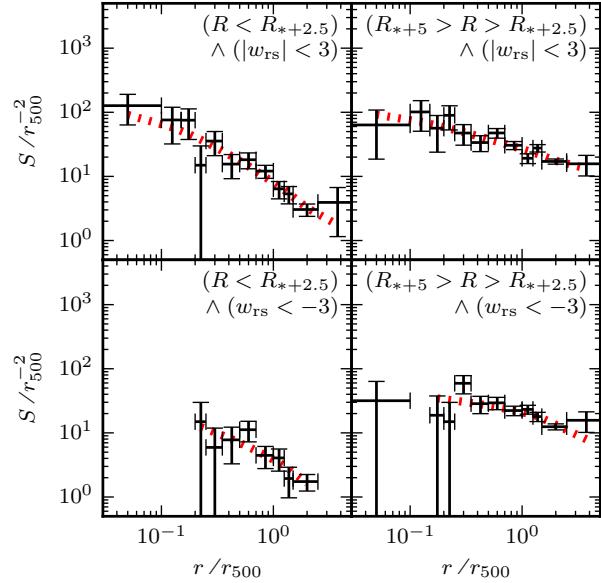


Figure B8. Radial density profiles for RXC J0821.8+0112. The lines are the same as described in Figure B1.

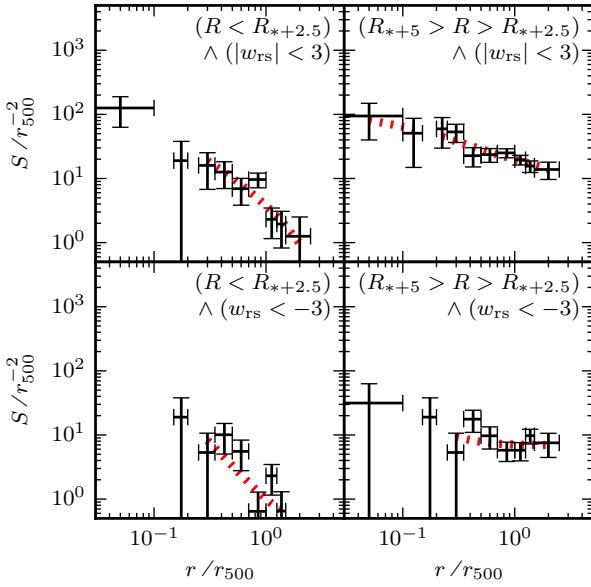


Figure B9. Radial density profiles for RXC J2023.0–2056. The lines are the same as described in Figure B1.

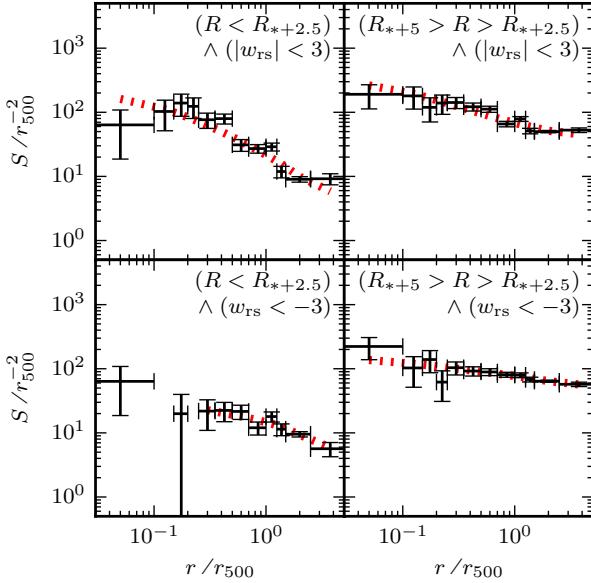


Figure B10. Radial density profiles for RXC J2048.1–1750. The lines are the same as described in Figure B1.

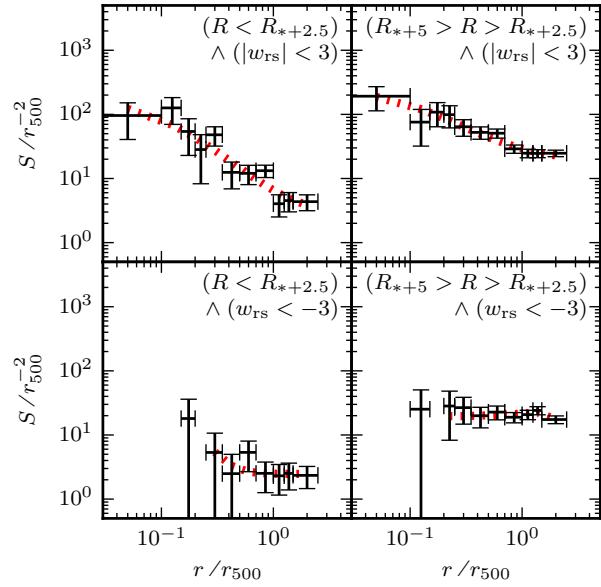


Figure B11. Radial density profiles for RXC J2129.8–5048. The lines are the same as described in Figure B1.

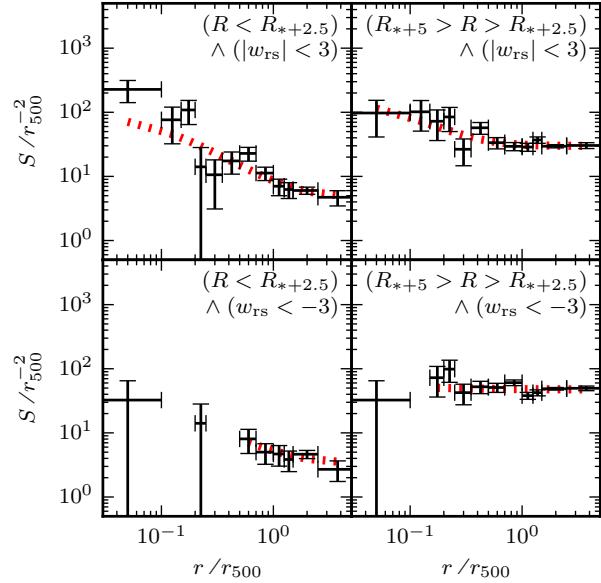


Figure B12. Radial density profiles for RXC J2218.6–3853. The lines are the same as described in Figure B1.

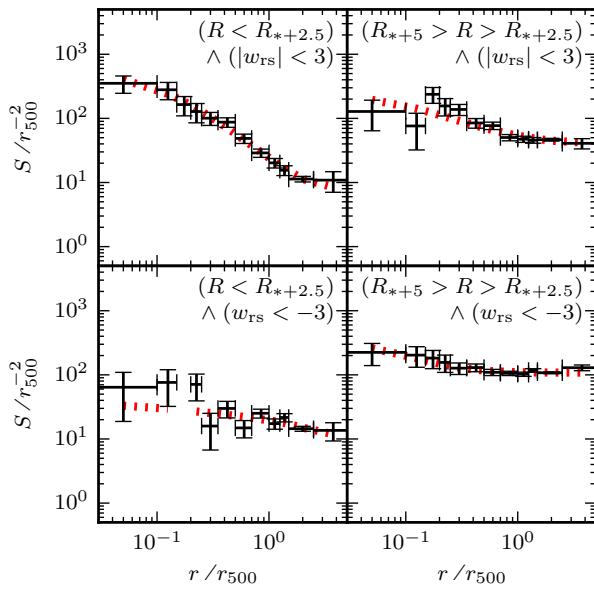


Figure B13. Radial density profiles for RXC J2234.5–3744. The lines are the same as described in Figure B1.

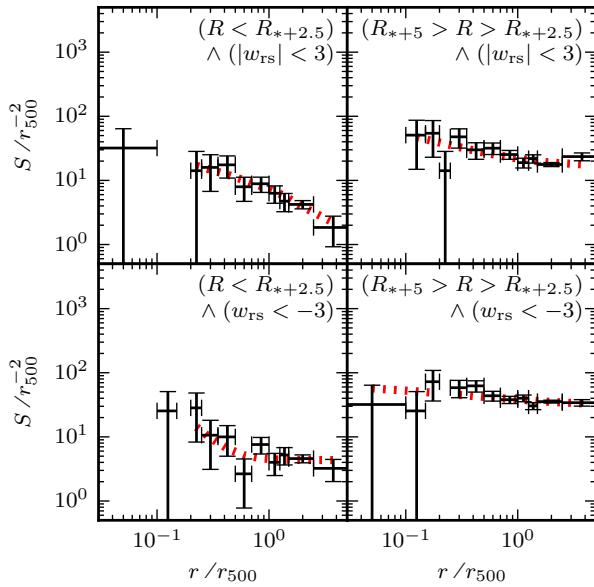


Figure B14. Radial density profiles for RXC J2319.6–7313. The lines are the same as described in Figure B1.

Table B1. NFW fitting results.

Object	Galaxy filter	β	S_0 r_{500}^{-3}	S_{bgNFW} r_{500}^{-2}
RXC J0006.0–3443	Bright, red	2.7 ± 0.5	49.7 ± 9.0	7.2 ± 2.1
RXC J0049.4–2931	Bright, red	3.4 ± 0.5	59.0 ± 10.9	1.9 ± 0.5
RXC J0345.7–4112	Bright, red	3.2 ± 1.0	12.2 ± 4.5	2.3 ± 0.6
RXC J0547.6–3152	Bright, red	2.67 ± 0.35	50.1 ± 6.8	5.4 ± 1.4
RXC J0605.8–3518	Bright, red	3.2 ± 0.4	55.5 ± 8.8	7.2 ± 0.8
RXC J0616.8–4748	Bright, red	2.58 ± 0.26	30.1 ± 3.4	2.7 ± 0.5
RXC J0645.4–5413	Bright, red	2.74 ± 0.29	96.2 ± 13.0	9.8 ± 1.5
RXC J0821.8+0112	Bright, red	2.5 ± 0.4	25.8 ± 4.0	1.8 ± 0.9
RXC J2023.0–2056	Bright, red	2.7 ± 0.7	23.6 ± 5.9	0.2 ± 1.5
RXC J2048.1–1750	Bright, red	2.3 ± 0.5	37.3 ± 7.7	5.8 ± 2.2
RXC J2129.8–5048	Bright, red	3.3 ± 0.7	46.1 ± 10.7	3.3 ± 1.4
RXC J2218.6–3853	Bright, red	2.9 ± 1.0	20.1 ± 6.4	5.1 ± 1.1
RXC J2234.5–3744	Bright, red	3.18 ± 0.15	129.4 ± 6.9	8.4 ± 0.8
RXC J2319.6–7313	Bright, red	1.6 ± 0.4	4.5 ± 0.9	2.2 ± 0.5
RXC J0006.0–3443	Faint, red	2.0 ± 0.5	20.5 ± 3.6	36.1 ± 3.4
RXC J0049.4–2931	Faint, red	3.21 ± 0.30	59.7 ± 7.0	15.5 ± 0.7
RXC J0345.7–4112	Faint, red	2.8 ± 0.9	39.7 ± 12.5	5.4 ± 3.1
RXC J0547.6–3152	Faint, red	2.4 ± 0.6	33.5 ± 7.6	25.5 ± 3.3
RXC J0605.8–3518	Faint, red	2.8 ± 0.6	45.6 ± 10.3	33.7 ± 2.1
RXC J0616.8–4748	Faint, red	2.3 ± 0.7	22.3 ± 6.6	26.8 ± 2.6
RXC J0645.4–5413	Faint, red	1.6 ± 0.5	27.6 ± 6.5	44.0 ± 4.6
RXC J0821.8+0112	Faint, red	1.7 ± 0.5	15.1 ± 3.2	13.3 ± 3.1
RXC J2023.0–2056	Faint, red	2.1 ± 0.7	16.7 ± 3.9	12.1 ± 3.9
RXC J2048.1–1750	Faint, red	2.3 ± 0.5	51.4 ± 10.0	45.6 ± 4.2
RXC J2129.8–5048	Faint, red	2.8 ± 0.5	54.2 ± 8.9	21.2 ± 2.7
RXC J2218.6–3853	Faint, red	3.9 ± 1.5	36.0 ± 17.8	29.9 ± 1.6
RXC J2234.5–3744	Faint, red	2.6 ± 0.7	40.4 ± 10.2	42.1 ± 4.0
RXC J2319.6–7313	Faint, red	2.3 ± 1.3	11.2 ± 4.8	17.8 ± 2.1
RXC J0006.0–3443	Bright, blue	1.7 ± 0.9	4.9 ± 1.4	5.9 ± 1.7
RXC J0049.4–2931	Bright, blue	1.2 ± 1.2	1.4 ± 0.9	2.0 ± 0.8
RXC J0345.7–4112	Bright, blue	6.6 ± 2.1	$(1.8 \pm 1.0) \times 10^2$	0.96 ± 0.20
RXC J0547.6–3152	Bright, blue	4.4 ± 6.1	$(2.6 \pm 3.8) \times 10^1$	6.3 ± 1.2
RXC J0605.8–3518	Bright, blue	9.4 ± 13.0	$(1.4 \pm 2.5) \times 10^2$	6.8 ± 0.5
RXC J0616.8–4748	Bright, blue	2.9 ± 1.3	7.3 ± 3.5	3.8 ± 0.6
RXC J0645.4–5413	Bright, blue	$(0.1 \pm 2.4) \times 10^2$	$(0.5 \pm 6.5) \times 10^2$	9.7 ± 0.7
RXC J0821.8+0112	Bright, blue	2.0 ± 0.9	5.2 ± 1.7	0.8 ± 1.0
RXC J2023.0–2056	Bright, blue	4.1 ± 2.5	33.9 ± 21.7	0.4 ± 1.2
RXC J2048.1–1750	Bright, blue	1.1 ± 0.5	3.4 ± 1.0	5.9 ± 1.1
RXC J2129.8–5048	Bright, blue	7.5 ± 3.3	$(1.6 \pm 1.4) \times 10^2$	2.47 ± 0.26
RXC J2218.6–3853	Bright, blue	2.7 ± 0.9	7.3 ± 3.1	3.6 ± 0.5
RXC J2234.5–3744	Bright, blue	1.0 ± 1.4	2.4 ± 1.2	11.9 ± 3.7
RXC J2319.6–7313	Bright, blue	5.3 ± 2.6	55.2 ± 34.1	4.3 ± 0.5
RXC J0006.0–3443	Faint, blue	-0.6 ± 0.6	0.99 ± 0.28	38.2 ± 10.6
RXC J0049.4–2931	Faint, blue	3.0 ± 0.7	20.4 ± 5.8	29.9 ± 0.9
RXC J0345.7–4112	Faint, blue	$(2.0 \pm 5.0) \times 10^1$	$(0.0 \pm 1.7) \times 10^6$	7.7 ± 0.4
RXC J0547.6–3152	Faint, blue	0.4 ± 0.7	2.6 ± 1.0	44.5 ± 4.7
RXC J0605.8–3518	Faint, blue	1.8 ± 3.2	3.6 ± 5.1	70.4 ± 4.4
RXC J0616.8–4748	Faint, blue	-1.1 ± 1.1	0.10 ± 0.08	37.3 ± 2.7
RXC J0645.4–5413	Faint, blue	0.6 ± 1.0	1.5 ± 0.8	76.2 ± 2.0
RXC J0821.8+0112	Faint, blue	0.9 ± 0.7	3.6 ± 1.0	7.9 ± 3.6
RXC J2023.0–2056	Faint, blue	4.4 ± 3.9	14.8 ± 21.4	6.9 ± 1.3
RXC J2048.1–1750	Faint, blue	1.4 ± 0.4	11.7 ± 2.0	56.9 ± 2.6
RXC J2129.8–5048	Faint, blue	-1.5 ± 0.5	0.078 ± 0.029	0.7 ± 10.5
RXC J2218.6–3853	Faint, blue	2.6 ± 13.3	1.5 ± 8.1	47.6 ± 3.2
RXC J2234.5–3744	Faint, blue	4.4 ± 1.4	70.2 ± 32.7	108.4 ± 2.5
RXC J2319.6–7313	Faint, blue	1.5 ± 1.3	4.0 ± 2.4	33.3 ± 2.9

**APPENDIX C: BACKGROUND COUNT
DENSITY ANALYSIS**

The background count densities for all of the objects, using the four main galaxy population filters are shown in Table C1.

Table C1. Background count density measurements. In the case of the RXC J2023.0-2056 bright blue filter, no objects are detected in the region used for measuring $S_{\text{bg simple}}$.

Object	Galaxy filter	$S_{\text{bg simple}}$ arcmin $^{-2}$	$\alpha S_{\text{bg sector}}$ arcmin $^{-2}$	$S_{\text{bg NFW}}$ arcmin $^{-2}$	$S_{\text{bg simple}}/S_{\text{bg NFW}}$
RXC J0006.0-3443	Bright, red	0.166 ± 0.020	0.02	0.12 ± 0.04	1.34
RXC J0006.0-3443	Faint, red	0.70 ± 0.04	0.04	0.62 ± 0.06	1.12
RXC J0006.0-3443	Bright, blue	0.128 ± 0.017	0.02	0.102 ± 0.029	1.25
RXC J0006.0-3443	Faint, blue	1.14 ± 0.05	0.07	0.66 ± 0.18	1.73
RXC J0049.4-2931	Bright, red	0.064 ± 0.011	0.01	0.051 ± 0.013	1.25
RXC J0049.4-2931	Faint, red	0.427 ± 0.027	0.03	0.411 ± 0.019	1.04
RXC J0049.4-2931	Bright, blue	0.074 ± 0.011	0.01	0.054 ± 0.022	1.38
RXC J0049.4-2931	Faint, blue	0.81 ± 0.04	0.04	0.795 ± 0.024	1.02
RXC J0345.7-4112	Bright, red	0.029 ± 0.010	0.01	0.027 ± 0.007	1.08
RXC J0345.7-4112	Faint, red	0.095 ± 0.019	0.02	0.06 ± 0.04	1.50
RXC J0345.7-4112	Bright, blue	0.011 ± 0.006	0.00	0.0111 ± 0.0024	0.98
RXC J0345.7-4112	Faint, blue	0.098 ± 0.019	0.02	0.089 ± 0.004	1.11
RXC J0547.6-3152	Bright, red	0.182 ± 0.024	0.05	0.134 ± 0.034	1.35
RXC J0547.6-3152	Faint, red	0.71 ± 0.05	0.06	0.63 ± 0.08	1.13
RXC J0547.6-3152	Bright, blue	0.179 ± 0.024	0.05	0.155 ± 0.030	1.15
RXC J0547.6-3152	Faint, blue	1.26 ± 0.06	0.22	1.10 ± 0.12	1.14
RXC J0605.8-3518	Bright, red	0.209 ± 0.019	0.03	0.184 ± 0.020	1.13
RXC J0605.8-3518	Faint, red	0.90 ± 0.04	0.06	0.87 ± 0.05	1.03
RXC J0605.8-3518	Bright, blue	0.180 ± 0.017	0.02	0.175 ± 0.014	1.03
RXC J0605.8-3518	Faint, blue	1.84 ± 0.06	0.06	1.81 ± 0.11	1.01
RXC J0616.8-4748	Bright, red	0.087 ± 0.012	0.01	0.060 ± 0.012	1.44
RXC J0616.8-4748	Faint, red	0.644 ± 0.033	0.04	0.60 ± 0.06	1.07
RXC J0616.8-4748	Bright, blue	0.088 ± 0.012	0.03	0.086 ± 0.013	1.03
RXC J0616.8-4748	Faint, blue	0.99 ± 0.04	0.05	0.84 ± 0.06	1.18
RXC J0645.4-5413	Bright, red	0.302 ± 0.022	0.08	0.231 ± 0.035	1.31
RXC J0645.4-5413	Faint, red	1.19 ± 0.04	0.07	1.04 ± 0.11	1.14
RXC J0645.4-5413	Bright, blue	0.225 ± 0.019	0.08	0.230 ± 0.016	0.98
RXC J0645.4-5413	Faint, blue	1.86 ± 0.06	0.07	1.81 ± 0.05	1.03
RXC J0821.8+0112	Bright, red	0.055 ± 0.011	0.02	0.031 ± 0.016	1.77
RXC J0821.8+0112	Faint, red	0.301 ± 0.027	0.03	0.23 ± 0.05	1.28
RXC J0821.8+0112	Bright, blue	0.029 ± 0.008	0.01	0.013 ± 0.017	2.13
RXC J0821.8+0112	Faint, blue	0.224 ± 0.023	0.02	0.14 ± 0.06	1.60
RXC J2023.0-2056	Bright, red	0.011 ± 0.011	0.01	0.002 ± 0.014	5.66
RXC J2023.0-2056	Faint, red	0.12 ± 0.04	0.04	0.106 ± 0.034	1.15
RXC J2023.0-2056	Bright, blue	0.0 ± 0	0.00	0.004 ± 0.010	0.00
RXC J2023.0-2056	Faint, blue	0.066 ± 0.027	0.02	0.061 ± 0.011	1.09
RXC J2048.1-1750	Bright, red	0.245 ± 0.022	0.05	0.16 ± 0.06	1.55
RXC J2048.1-1750	Faint, red	1.37 ± 0.05	0.08	1.24 ± 0.11	1.11
RXC J2048.1-1750	Bright, blue	0.238 ± 0.021	0.03	0.161 ± 0.029	1.48
RXC J2048.1-1750	Faint, blue	1.70 ± 0.06	0.06	1.54 ± 0.07	1.10
RXC J2129.8-5048	Bright, red	0.051 ± 0.014	0.01	0.038 ± 0.017	1.33
RXC J2129.8-5048	Faint, red	0.290 ± 0.034	0.07	0.248 ± 0.031	1.17
RXC J2129.8-5048	Bright, blue	0.027 ± 0.010	0.01	0.0289 ± 0.0031	0.95
RXC J2129.8-5048	Faint, blue	0.204 ± 0.028	0.04	0.01 ± 0.12	24.40
RXC J2218.6-3853	Bright, red	0.130 ± 0.015	0.02	0.115 ± 0.025	1.13
RXC J2218.6-3853	Faint, red	0.673 ± 0.034	0.05	0.678 ± 0.035	0.99
RXC J2218.6-3853	Bright, blue	0.095 ± 0.013	0.02	0.081 ± 0.011	1.18
RXC J2218.6-3853	Faint, blue	1.11 ± 0.04	0.04	1.08 ± 0.07	1.03
RXC J2234.5-3744	Bright, red	0.226 ± 0.022	0.02	0.169 ± 0.017	1.34
RXC J2234.5-3744	Faint, red	0.92 ± 0.04	0.04	0.84 ± 0.08	1.10
RXC J2234.5-3744	Bright, blue	0.288 ± 0.024	0.02	0.24 ± 0.07	1.21
RXC J2234.5-3744	Faint, blue	2.19 ± 0.07	0.06	2.17 ± 0.05	1.01
RXC J2319.6-7313	Bright, red	0.088 ± 0.012	0.01	0.051 ± 0.010	1.74
RXC J2319.6-7313	Faint, red	0.431 ± 0.028	0.02	0.41 ± 0.05	1.05
RXC J2319.6-7313	Bright, blue	0.101 ± 0.013	0.01	0.100 ± 0.011	1.00
RXC J2319.6-7313	Faint, blue	0.81 ± 0.04	0.06	0.77 ± 0.07	1.06